Surface Gravity Effects of Subterranean Tunnels

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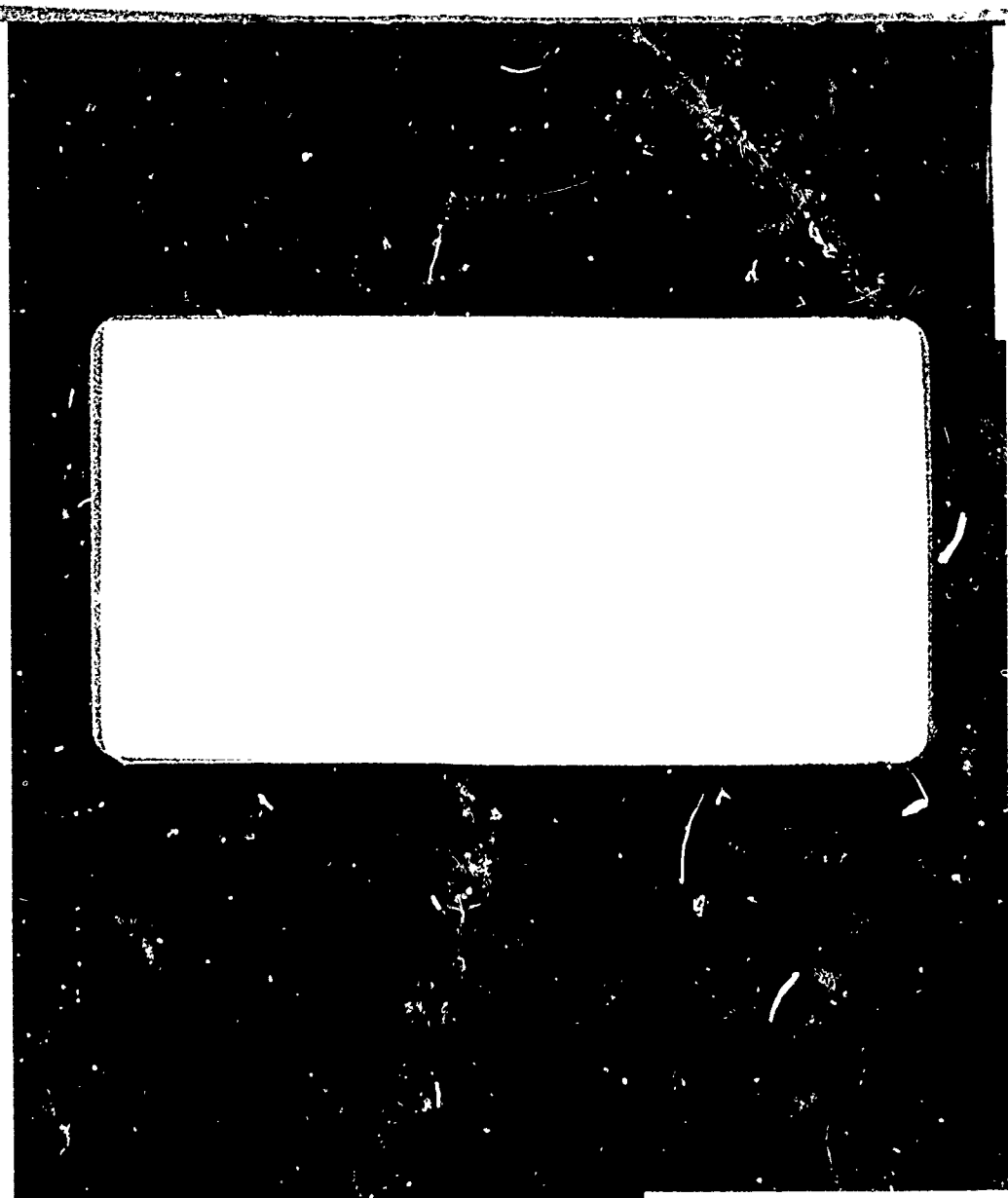

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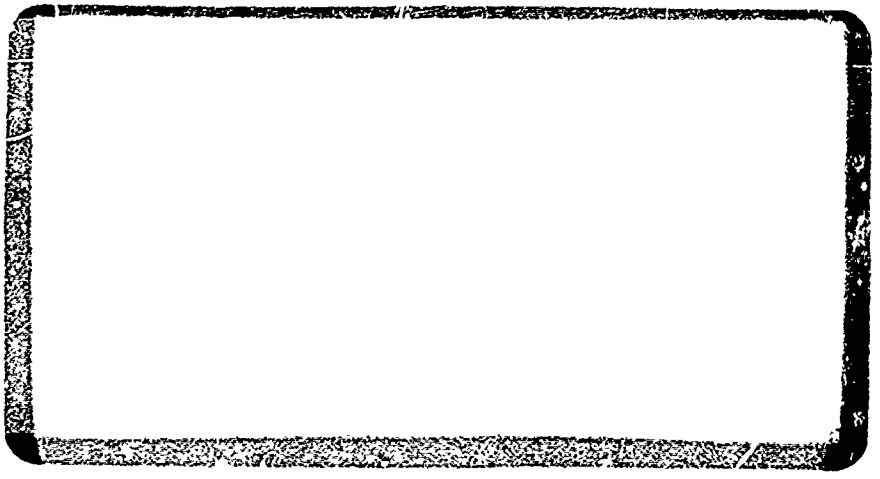

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report determines the change of six components of the symmetric second order tensor associated with the earth's gravity field as a result of the following mass changes and conditions: (1) A tunnel 16 km long is excavated 60 below the earth's surface; (2) A vehicle traveling at a constant speed crosses the tunnel at the earth's surface; (3) The resulting tensor component changes are computed and plotted; (4) The computations are repeated for tunnel depths of 30 and 90 m; and (5) The problem may be inverted from one of subsurface mass removal to one of mass addition above the earth's surface. The results of the report

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determine that (1) gradiometric detection of large tunnels to a depth of 30 m is feasible, (2) reliable detection of large tunnels deeper than 30 m imposes moderately sophisticated data processing requirements, and (3) detection of tunnels deeper than 90 m is difficult.

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SURFACE GRAVITY EFFECTS OF SUBTERRANEAN TUNNELS

16 July 1976

Prepared for:

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
Fort Belvoir, Virginia 22060

Submitted in fulfillment of
Contract No. DAAG53-76-M-5908

THE ANALYTIC SCIENCES CORPORATION
Six Jacob Way
Reading, Massachusetts 01867

PROBLEM STATEMENT AND METHOD OF APPROACH

OVERVIEW

R-23881

- PROBLEM STATEMENT AND METHOD OF APPROACH
- ERROR SOURCES WHICH REDUCE DETECTABILITY
- RESULTS
- SUMMARY AND CONCLUSIONS

▼

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Contract Number DAAG53-76M-5509 dated 8 June 1976

Work Statement for Purchasing Order

DETERMINATION OF SECOND ORDER TENSOR CHANGE
AS A RESULT OF SPECIFIED MASS CHANGES

Determine the change of the six components of the symmetric second order tensor associated with the earth's gravity field as a result of the following mass changes and conditions:

1. A tunnel 16 km long and having a diameter of 5 m is excavated 6 m below the earth's surface, and the resulting mass with density $\rho = 2.6$ g cm^{-3} is removed to infinity.

2. A vehicle traveling at the constant speed of 10 km h^{-1} crosses the tunnel at the earth's surface 7 km from a tunnel end point at intersection angles of 90°, 60°, and 30°.

3. The resulting tensor component changes should be computed and plotted as a function of time and for changes equal or greater than 10^{-2} Eotvos.

4. The computations specified above should be repeated for the tunnel depths of 30 m and 90 m.

5. For the purpose of computational simplicity, the problem may be inverted from one of subsurface mass removal to one of mass addition above the earth's surface.

GRADIOMETRIC DETECTION OF HORIZONTAL SUBTERRANEAN TUNNELS – PROBLEM DEFINITION

R-23872

HOW FEASIBLE IS TUNNEL DETECTION BASED ON SURFACE GRAVITY GRADIENT MEASUREMENTS?

"QUICK LOOK" ANALYSIS INPUTS (SPECIFIED IN SOW)

- CYLINDRICAL TUNNEL DEPTH (y) = 6 m, 30 m, 90 m
- TUNNEL RADIUS (a) = 2.5 m
- TUNNEL LENGTH ($2z_o + \Delta z$) = 16 km
- GRADIOMETER VEHICLE VELOCITY = 10 km/hr
- ANGLE BETWEEN VEHICLE TRACK AND TUNNEL AXIS (HORIZONTAL PROJECTION) = 30^o, 60^o, 90^o
- DISTANCE TO NEAREST TUNNEL END FROM AXIAL POINT BELOW THE SURFACE POINT AT WHICH VEHICLE CROSSES (z_o) = 7 km (Figure on next page.)
- FLAT TERRAIN

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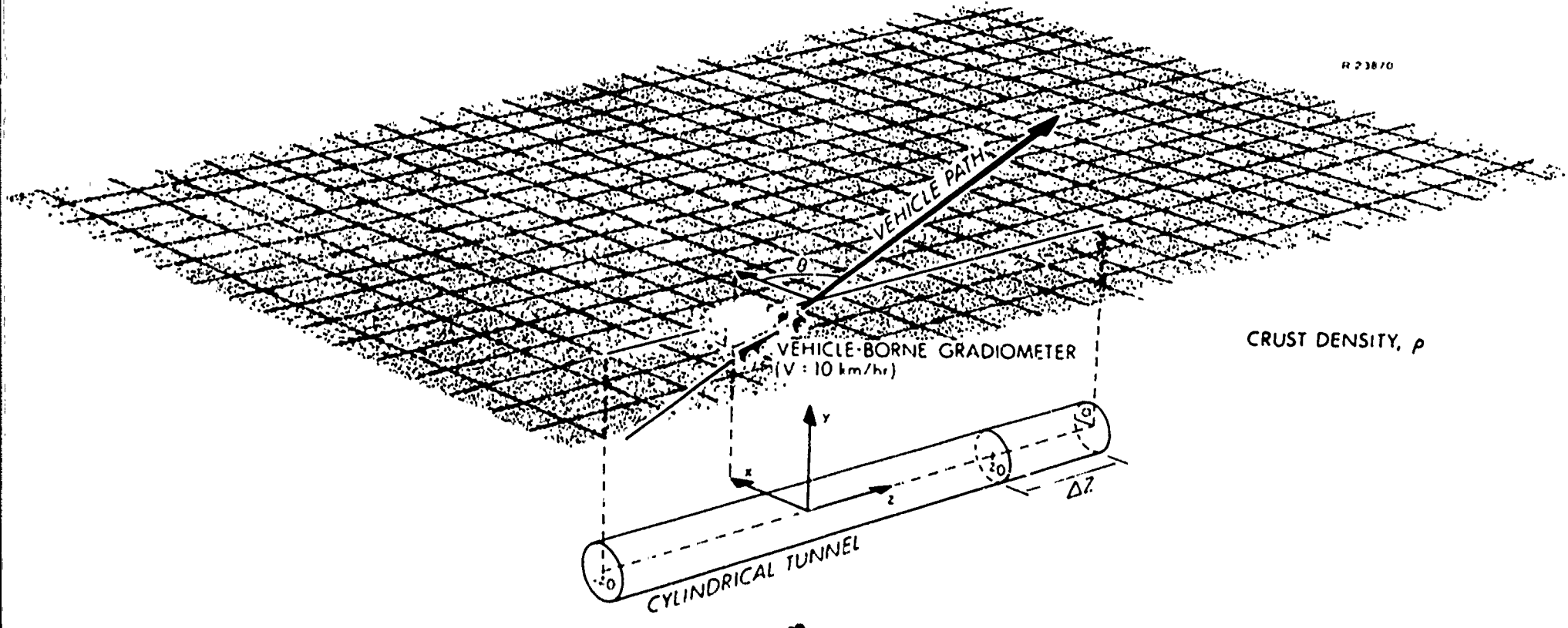
GRADIOMETRIC TUNNEL DETECTION GEOMETRY



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METHOD OF ANALYSIS

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- DIVIDE PROBLEM INTO EQUAL LENGTH CYLINDERS ON EACH SIDE OF CROSSING POINT. TREAT ASYMMETRICAL EXTENSION TO ONE END SEPARATELY
- TAKE ADVANTAGE OF FAVORABLE AXIAL ASPECT RATIO VIA GAUSS' LAW TO FIND THE SYMMETRICAL GRAVITY FIELD BY SURFACE INTEGRATION
- MODEL THE (FAR-REMOVED) ASYMMETRICAL END EXTENSION AS A POINT MASS
- FIND THE GRADIENT FIELDS BY ANALYTIC DIFFERENTIATION
- POINT MASS MODEL PROVIDES UPPER BOUND ON EFFECT OF ASYMMETRICAL CYLINDER END SINCE ACTUAL FIELD ATTENUATES MORE SLOWLY THAN POINT MASS FIELD (DUE TO PRESENCE OF HIGHER ORDER SPHERICAL HARMONICS)
- USE ASYMMETRICAL FIELD CALCULATION TO MEASURE END EFFECTS NOT MODELED IN GAUSS' LAW SOLUTION OF SYMMETRICAL PROBLEM
- EXPRESS TOTAL GRADIENT AS SUM OF "SYMMETRICAL" AND "ASYMMETRICAL" TERMS
- TRANSFORM RESULTS INTO "ALONG-TRACK, UP, CROSS-TRACK" COORDINATES

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EQUATIONS OF THE GRAVITY FIELD

R-23985

SYMMETRICAL PORTION ($-z_o$ TO $+z_o$)

$$g_{sym} = \frac{2\pi a^2 \rho G}{x^2+y^2} \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} *$$

ASYMMETRICAL PORTION (z_o TO $z_o+\Delta z_o$)

$$g_{asy} = \frac{\pi a^2 \Delta z \rho G}{\left[x^2+y^2+\left(z-z_o-\frac{\Delta z}{2}\right)^2\right]^{3/2}} \begin{bmatrix} x \\ y \\ z-z_o-\frac{\Delta z}{2} \end{bmatrix}$$

WHERE G IS THE UNIVERSAL GRAVITATIONAL CONSTANT

*x, y, z COORDINATES

PREVIEW OF RESULTS FOR OPTIMAL ENCOUNTER GEOMETRY (MAGNITUDES ONLY)

R-23880

TUNNEL DEPTH (meters)	MAXIMUM GRAVITY DISTURBANCE COMPONENT (mgal)		MAXIMUM GRAVITY GRADIENT ELEMENT (EU)	
	SYMMETRIC	ASYMMETRIC	SYMMETRIC	ASYMMETRIC
6	1.1×10^{-1}	1.1×10^{-5}	190	2.8×10^{-5}
30	2.3×10^{-2}	1.2×10^{-5}	7.6	3.2×10^{-5}
90	7.6×10^{-3}	1.6×10^{-5}	0.84	4.8×10^{-5}

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ERROR SOURCES WHICH REDUCE DETECTABILITY

POSSIBLE ERROR SOURCES ADVERSE TO TUNNEL DETECTION

R-?3873

ERROR SOURCE	ERROR MAGNITUDE	IMPACT ON GRADIOMETRIC MEASUREMENT
GRADIOMETER ERROR		
WHITE NOISE (10 sec avg)	1* - 10 EU‡	NONE IF VEHICLE MOVES VERY SLOWLY OR HALTS FOR GRADIENT MEASUREMENT
LOW FREQUENCY RANDOMNESS	1 - 20† EU	SIGNIFICANT REDUCTION PROBABLE WITH OPTIMAL FILTERING
TUNNEL DEVIATION FROM HORIZONTAL, CYLINDRICAL GEOMETRY	UNKNOWN	PROBABLY NOT SEVERE EXCEPT FOR RIGHT ANGLE TURNS (GRADIENTS OF FINE STRUCTURE ATTENUATE RAPIDLY)
EARTH'S ANOMALOUS GRADIENT FIELD		
RMS VARIATION	10 - 30 EU	EFFECT WILL BE REDUCED SOMEWHAT DUE TO SHORT TRACK LENGTH
HIGH DENSITY LOCAL GRADIENT ANOMALIES (ORE BODIES, NATURAL CAVES)	POSSIBLY > 100 EU	MAY REQUIRE SIGNATURE CORRELATION TECHNIQUES FOR DISCRIMINATION

*GOAL FOR CURRENT GRADIOMETER DEVELOPMENT PROGRAMS

†BEST DEMONSTRATED TO DATE IN LABORATORY

‡ONE EOTVOS UNIT (EU) = 10^{-9} sec^{-2}

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APPROXIMATE EFFECT OF EARTH'S BACKGROUND GRADIENT FIELD

R-23879

TRACK LENGTH (meters)	RMS GRADIENT VARIATION (AVERAGED OVER TRACK - EU)
10	1 EU
50	2.2 EU
200	4.5 EU

BASED ON SIMPLIFIED ANALYSIS USING

- FIRST-ORDER MARKOV GRADIENT MODEL
- RMS GRADIENT = 20 EU
- GRADIENT CORRELATION DISTANCE = 4 km

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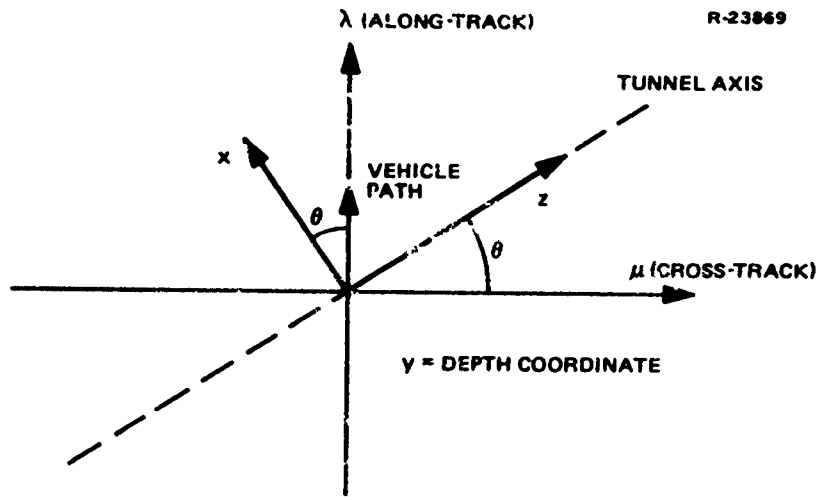
RESULTS

DEFINITIONS AND NOTATION



$$\underline{g} = \text{GRAVITY VECTOR} = \begin{pmatrix} g_\lambda \\ g_y \\ g_\mu \end{pmatrix}$$

$$\Gamma = \text{GRAVITY GRADIENT TENSOR} = \begin{bmatrix} \gamma_{\lambda\lambda} & \gamma_{\lambda y} & \gamma_{\lambda\mu} \\ \gamma_{y\lambda} & \gamma_{yy} & \gamma_{y\mu} \\ \gamma_{\mu\lambda} & \gamma_{\mu y} & \gamma_{\mu\mu} \end{bmatrix}$$

WHERE

$$\gamma_{\lambda\lambda} = \frac{\partial g_\lambda}{\partial \lambda} \qquad \gamma_{yy} = \frac{\partial g_y}{\partial y} \qquad \gamma_{\mu\mu} = \frac{\partial g_\mu}{\partial \mu}$$

$$\gamma_{\lambda y} = \frac{\partial g_\lambda}{\partial y} = \frac{\partial g_y}{\partial \lambda} \qquad \gamma_{\lambda\mu} = \frac{\partial g_\lambda}{\partial \mu} = \frac{\partial g_\mu}{\partial \lambda} \qquad \gamma_{y\mu} = \frac{\partial g_y}{\partial \mu} = \frac{\partial g_\mu}{\partial y}$$

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R-22926

GRAVITY VECTOR COMPONENTS
DEPTH = 6 METERS
0° AND 30° ENCOUNTER ANGLES

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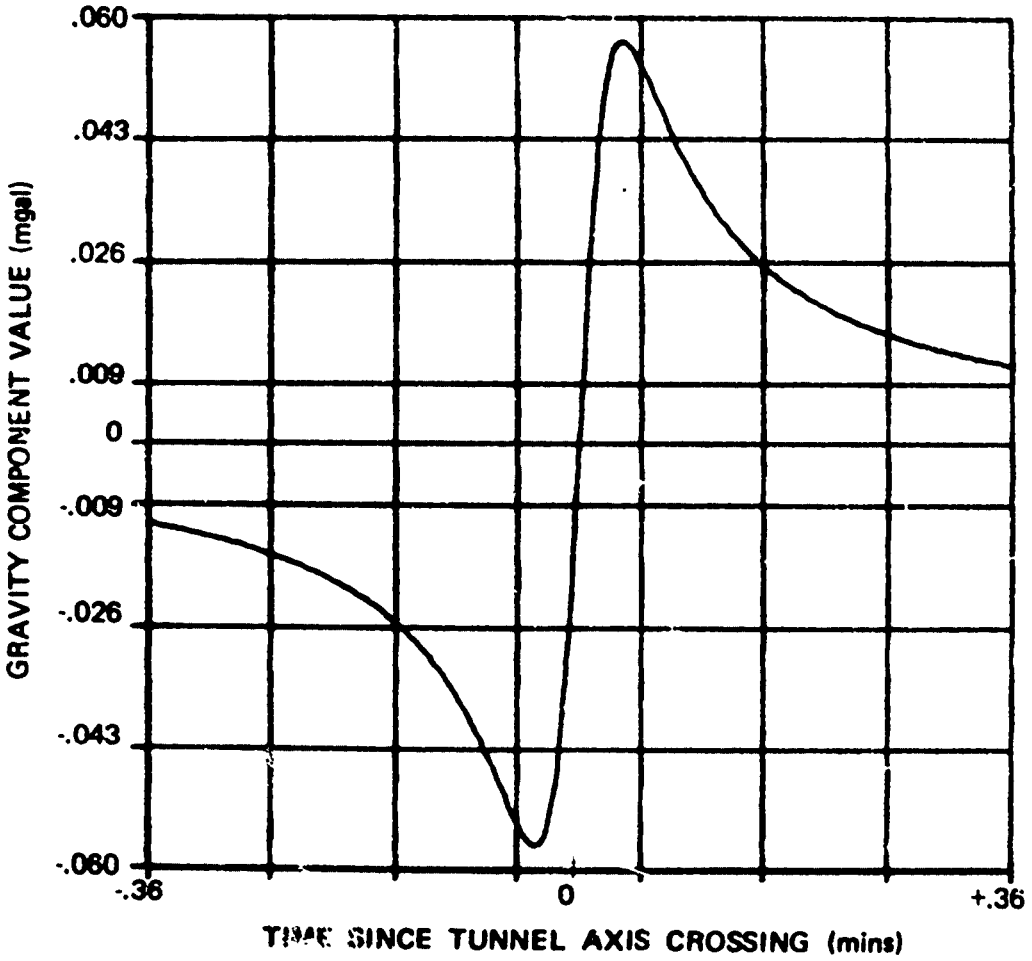
SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

R-23925



DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = g_λ

ENCOUNTER ANGLE (θ) = 0^o

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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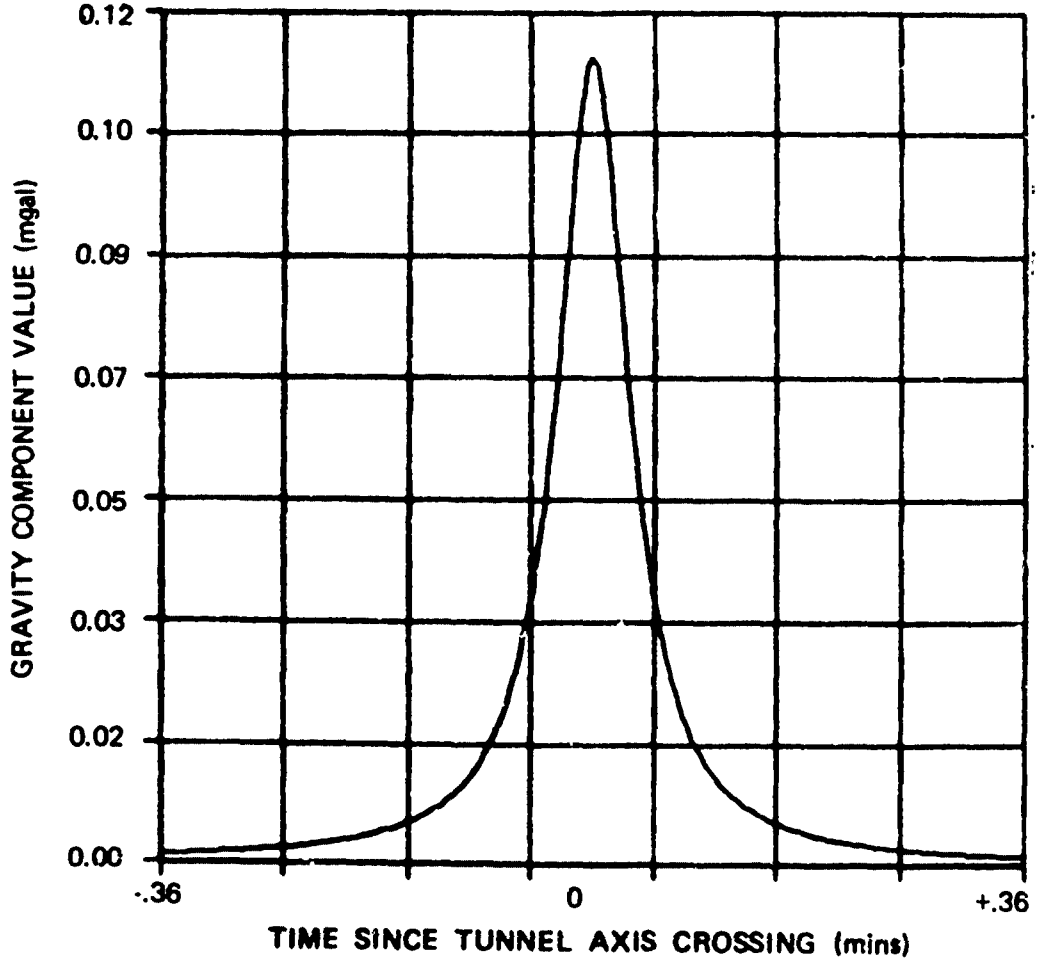
SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL R-23926



DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = g_y

ENCOUNTER ANGLE (θ) = 0^o

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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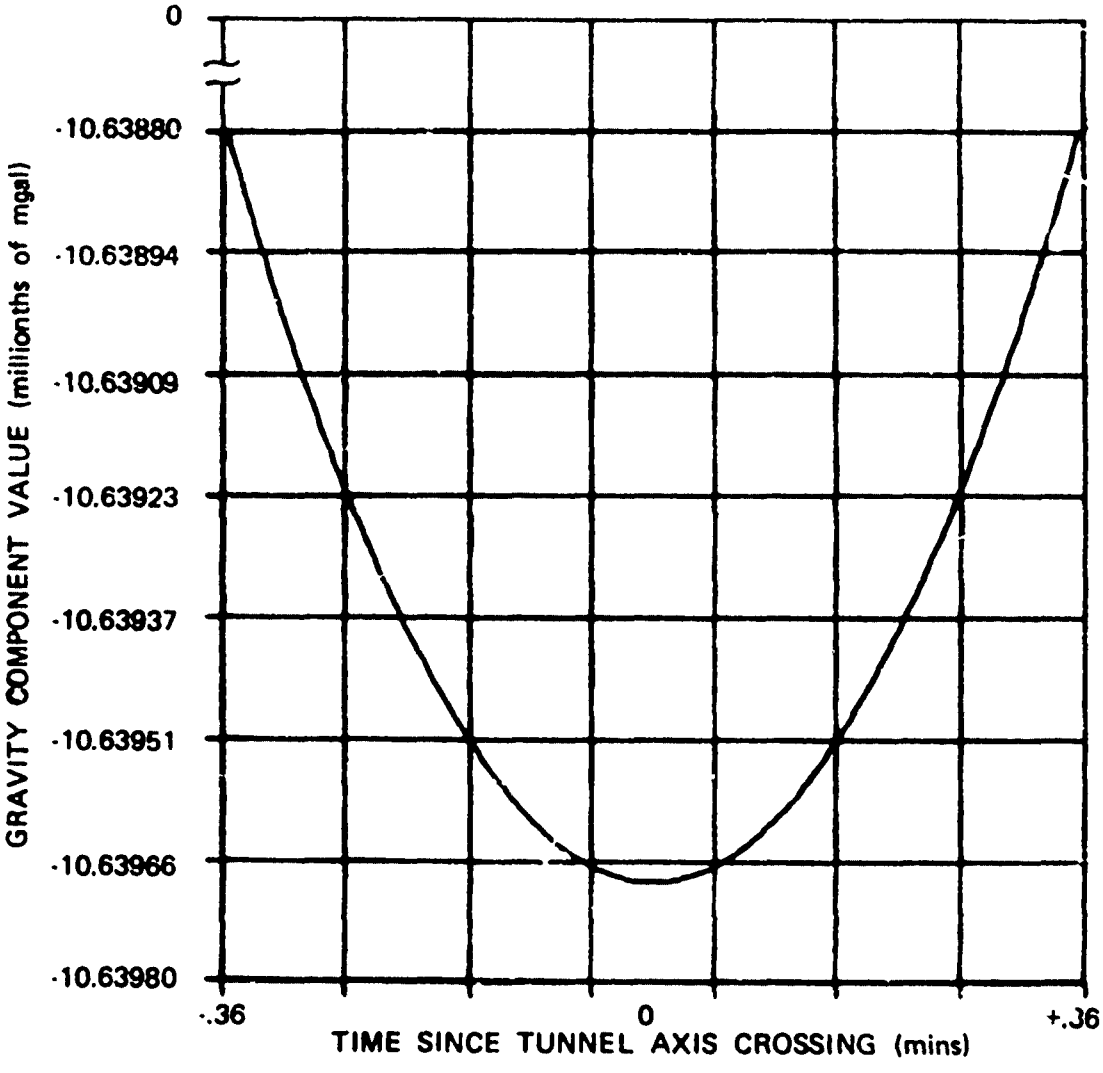
SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

R-23927



DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = g_μ

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

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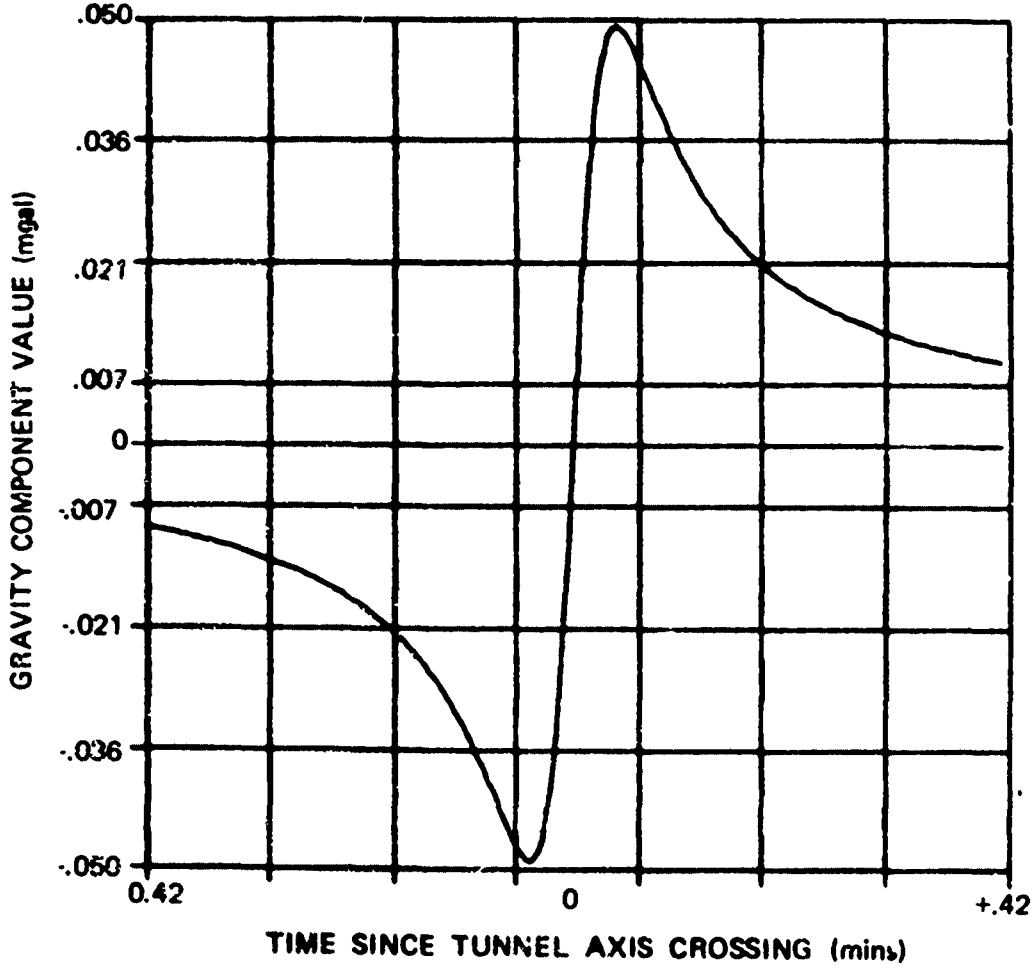

DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = g_λ

ENCOUNTER ANGLE (θ) = 30^0

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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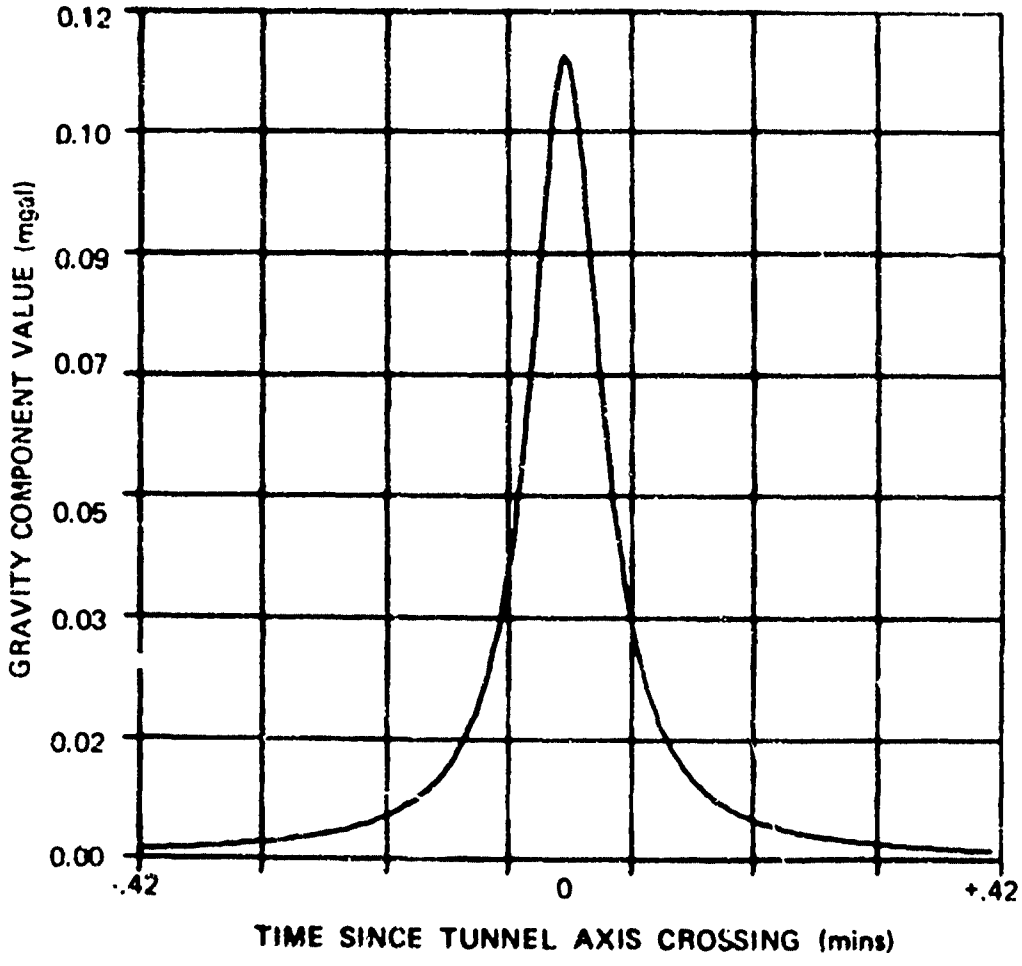
SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

R-23023



DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = g_y

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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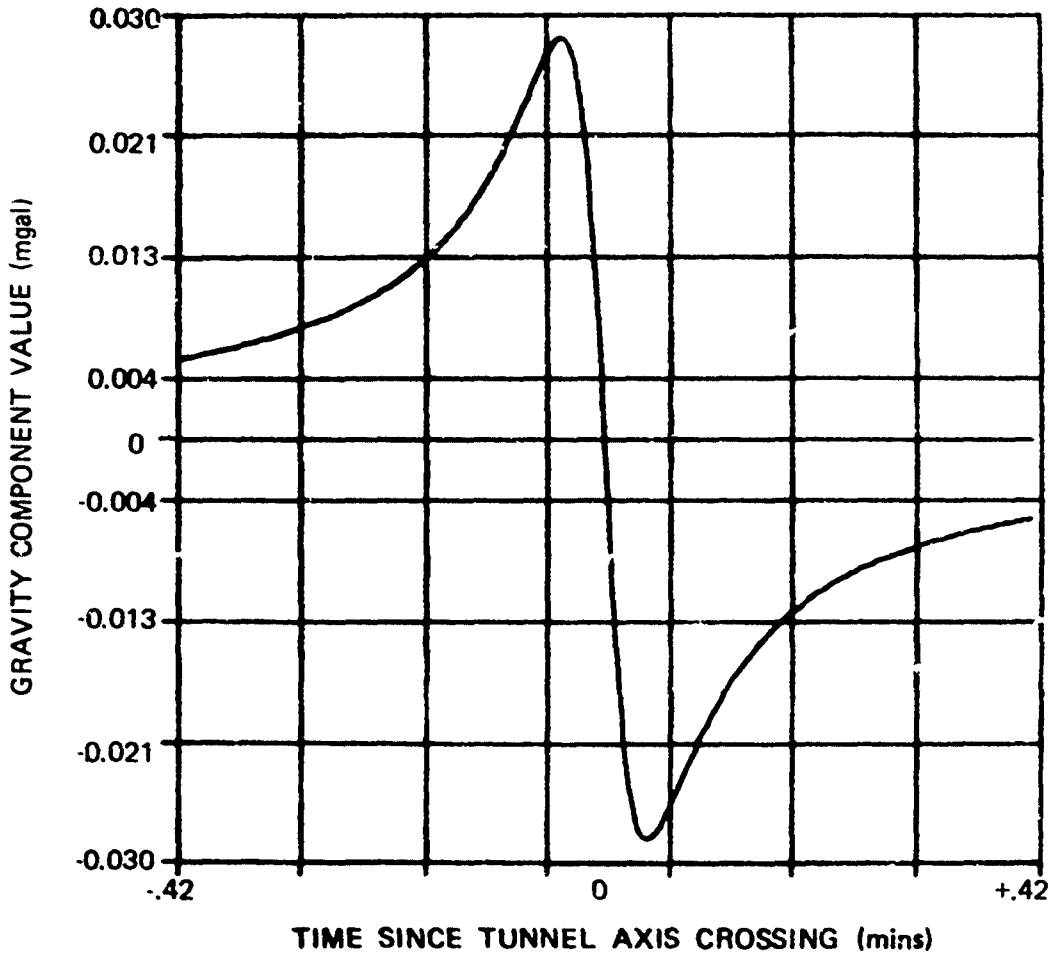
SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

R-23922



DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = g_μ

ENCOUNTER ANGLE (θ) = 30^o

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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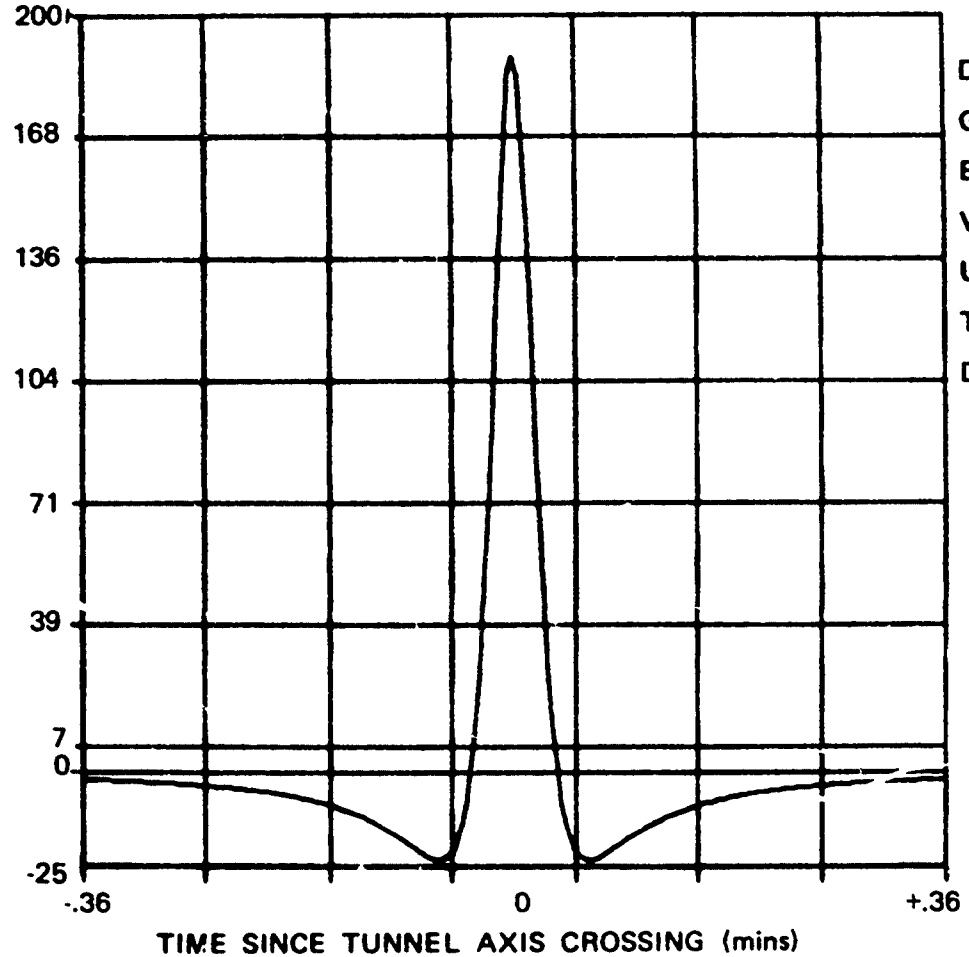
DEPTH = 6 METERS
0° ENCOUNTER ANGLE
(GRAVITY GRADIENTS)

R-23929

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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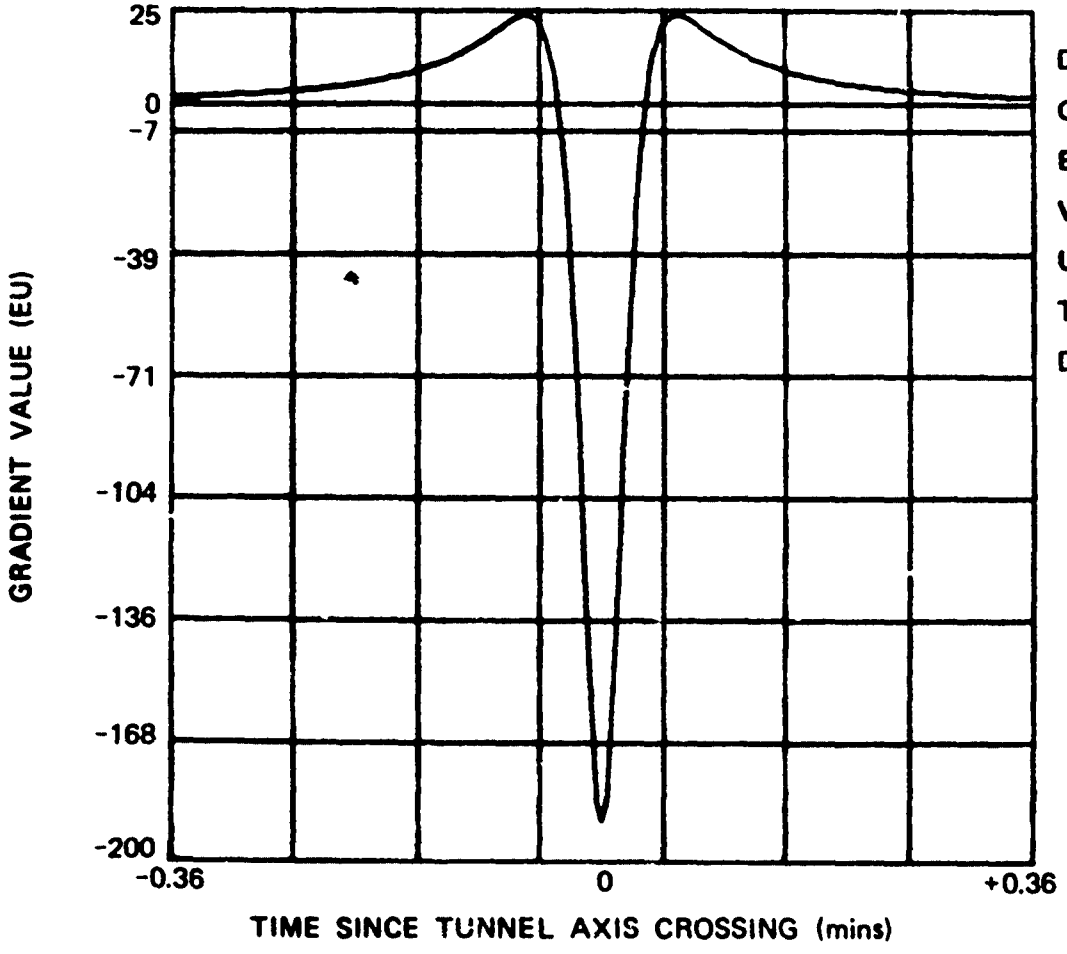
R-23930

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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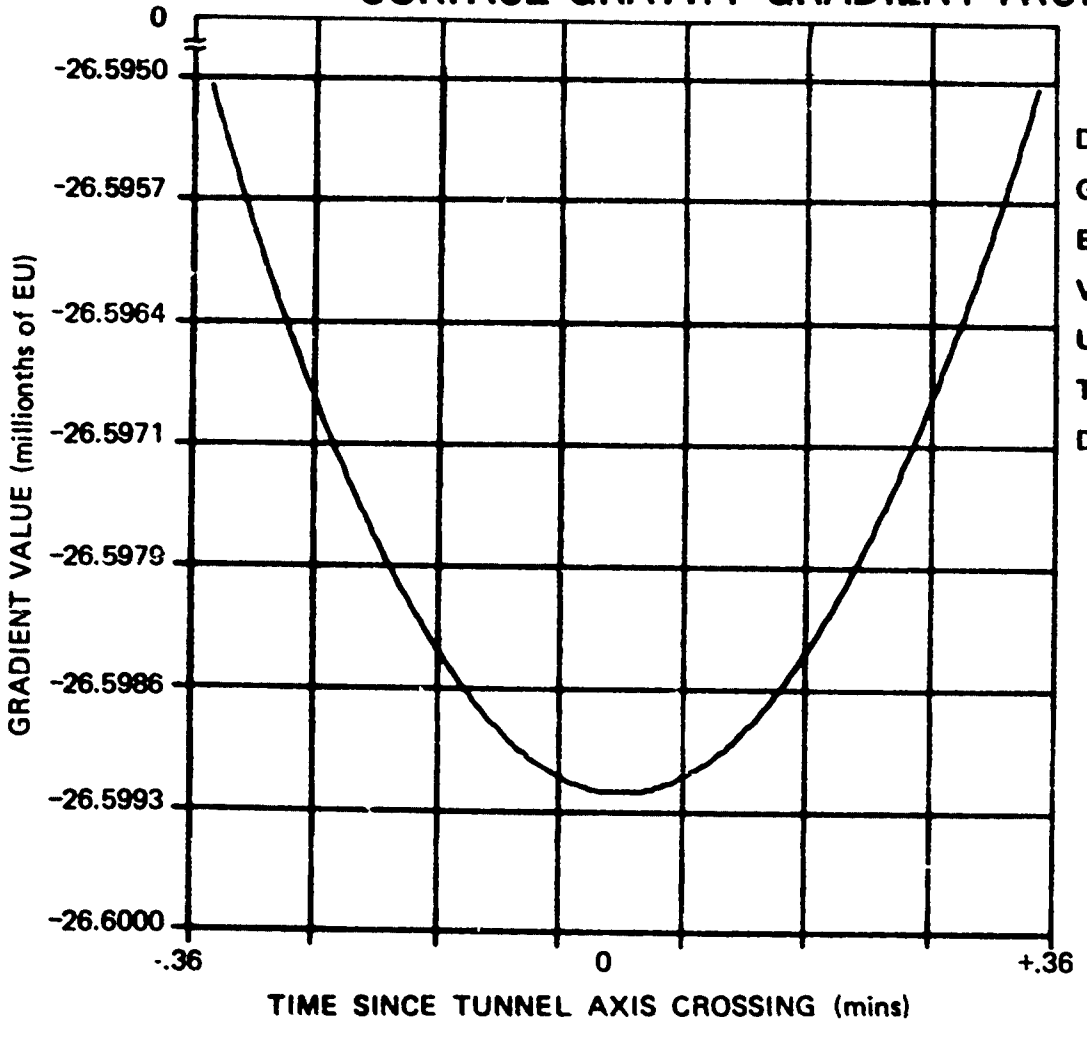
SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23943



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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SURFACE GRAVITY GRADIENT FROM TUNNEL

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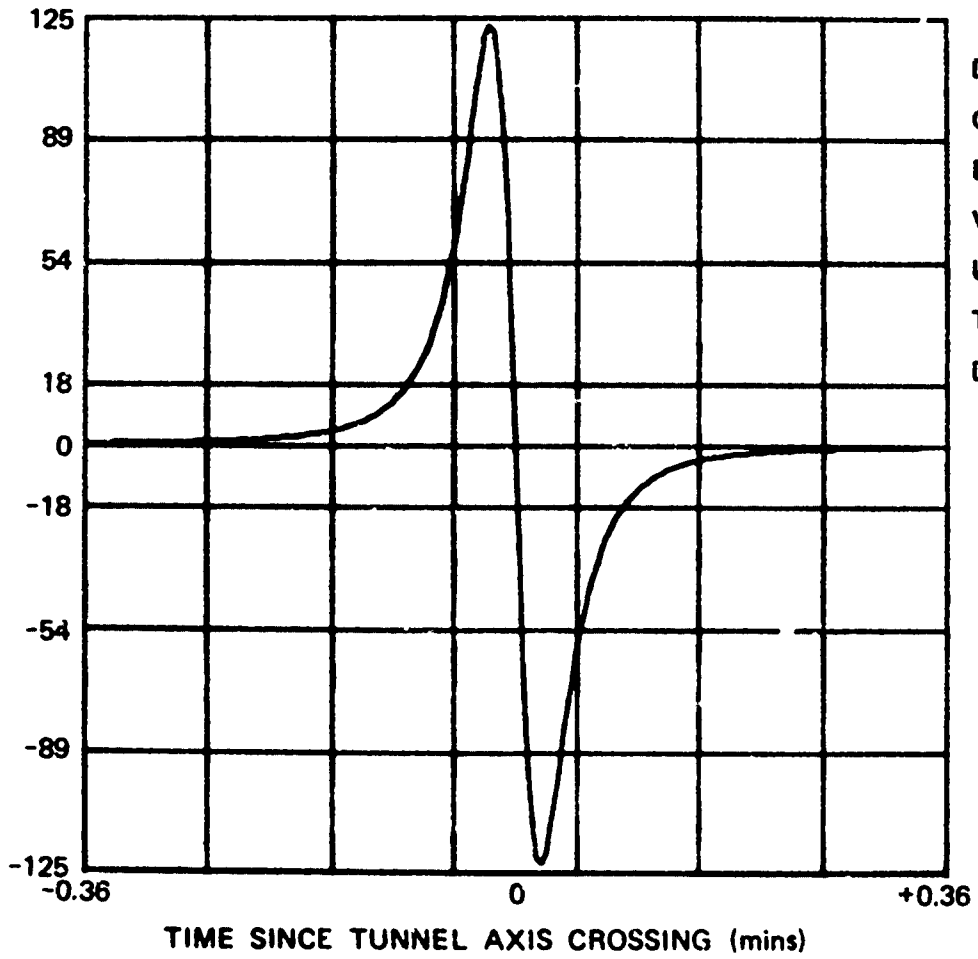

DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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SURFACE GRAVITY GRADIENT FROM TUNNEL

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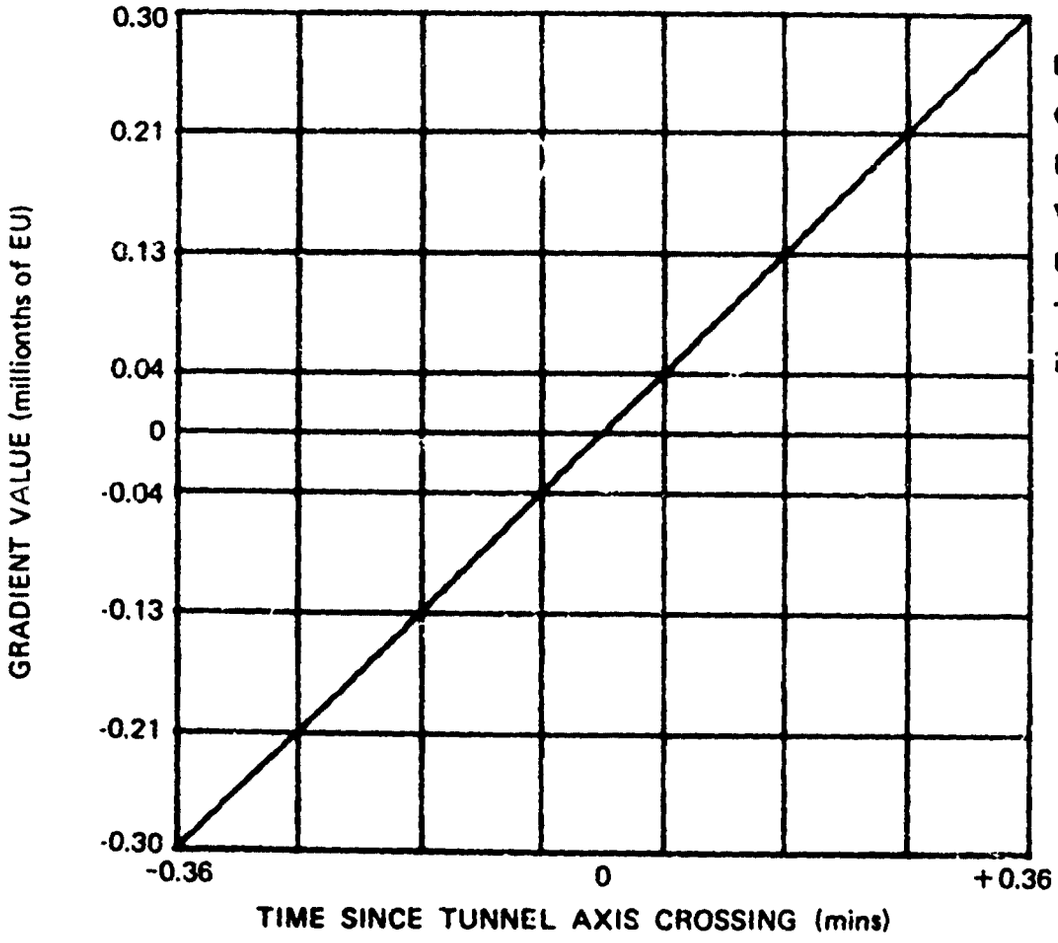

DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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SURFACE GRAVITY GRADIENT FROM TUNNEL

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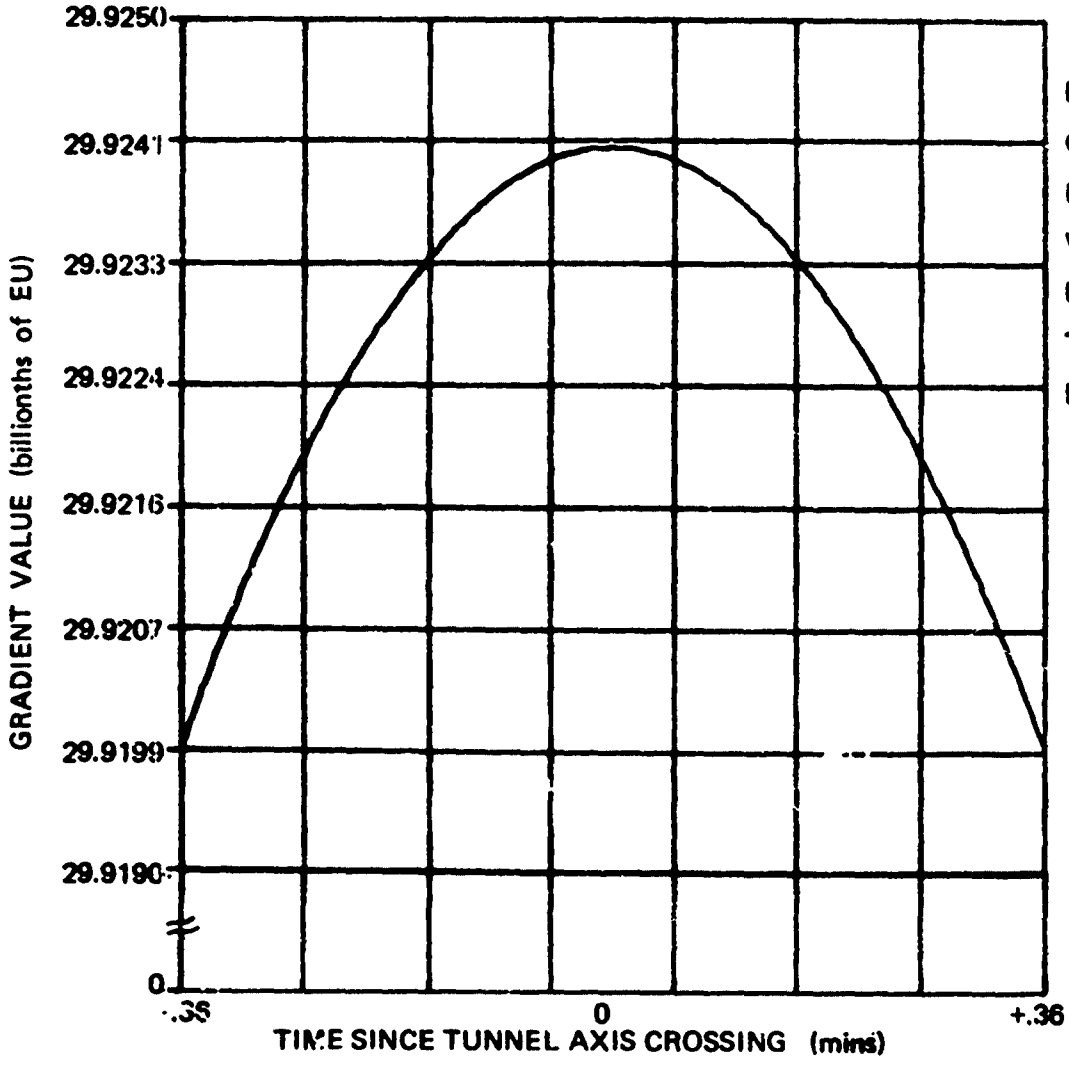


DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{yu}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

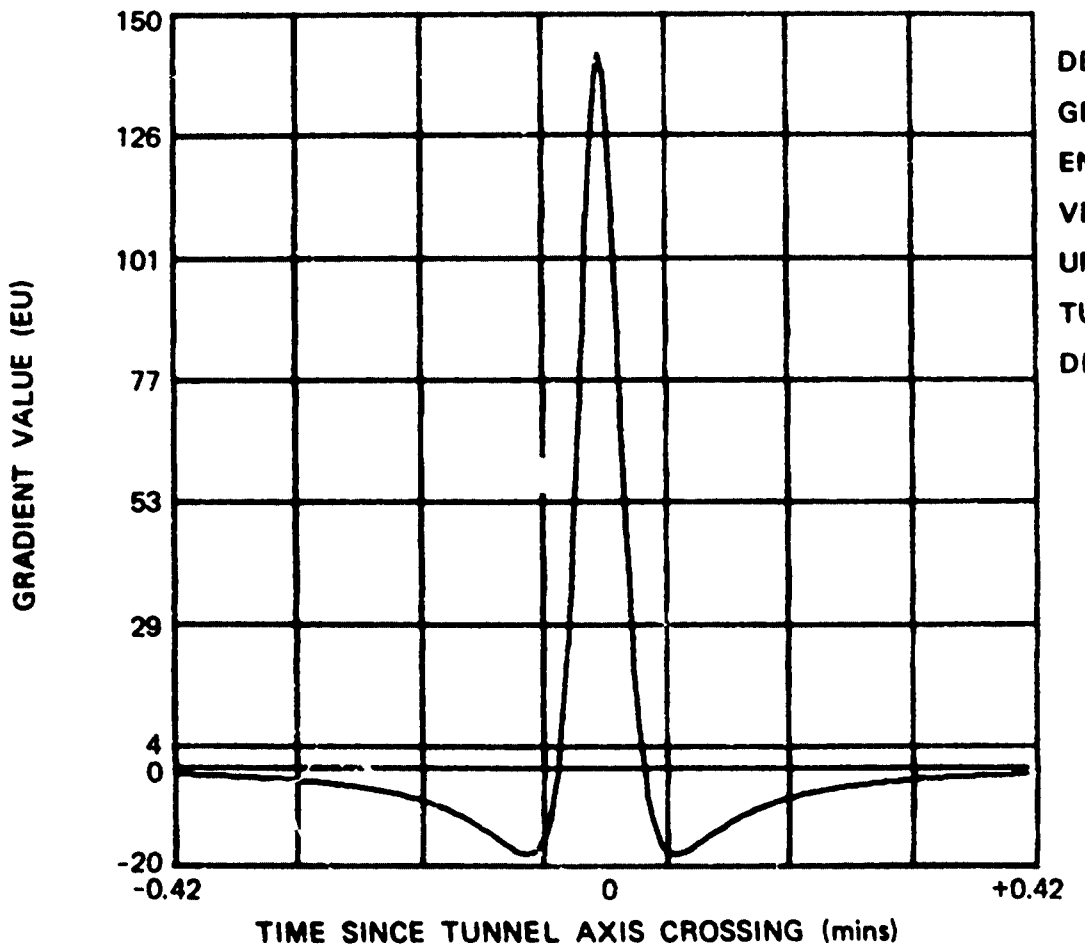
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 6 METERS
30° ENCOUNTER ANGLE

R-23936

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

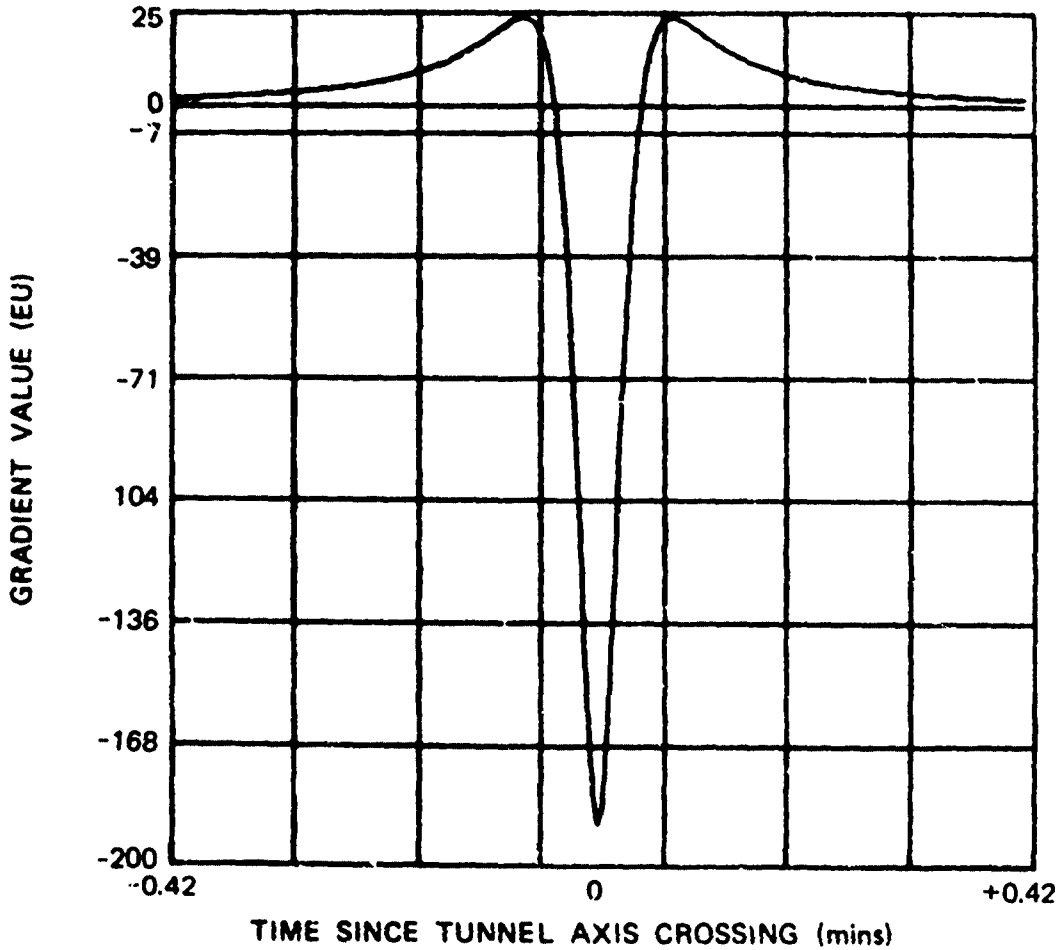
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23938



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

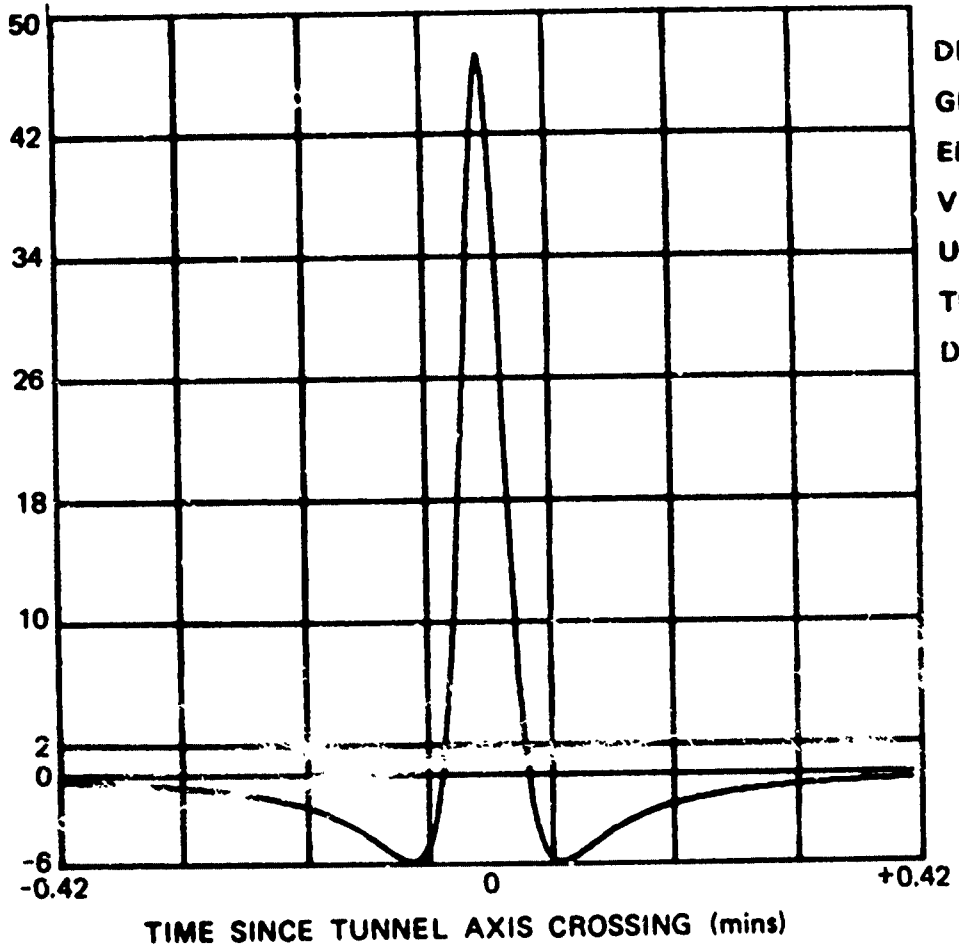
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23935



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{uu}

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

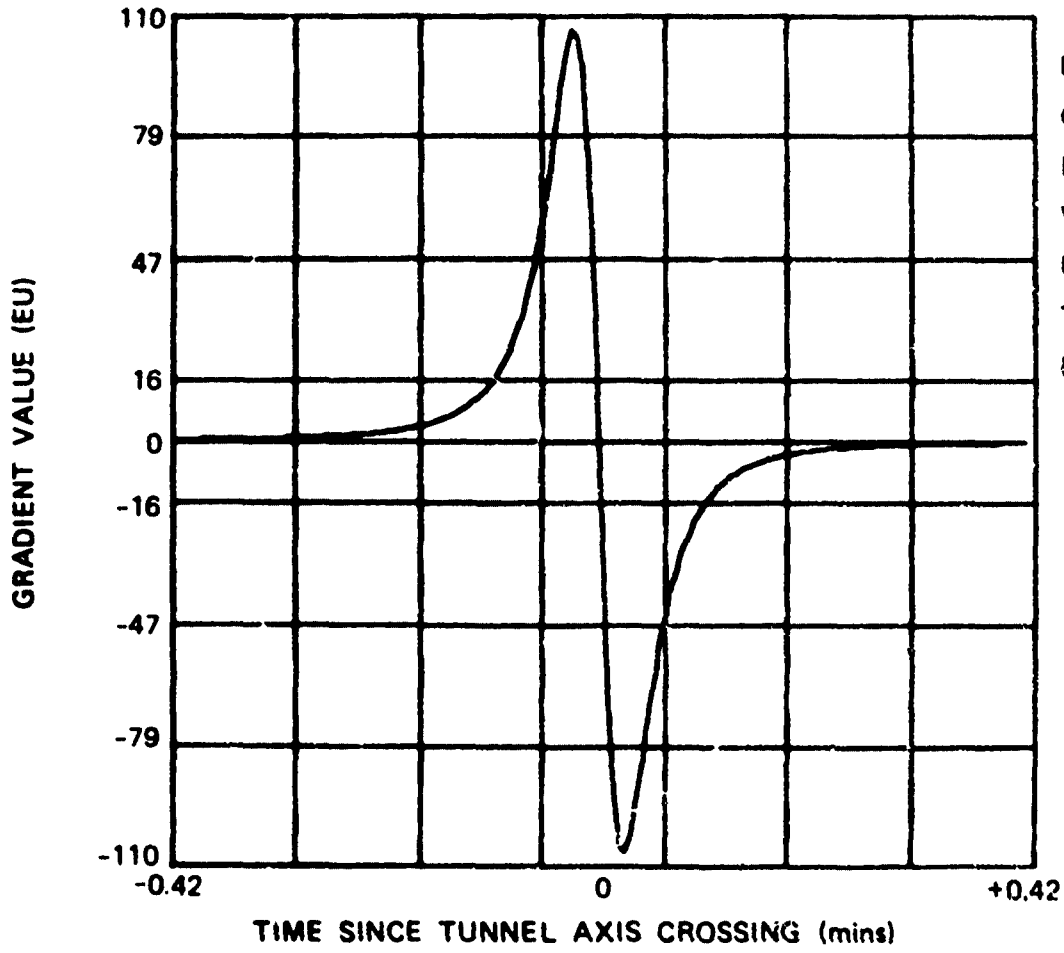
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23941



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

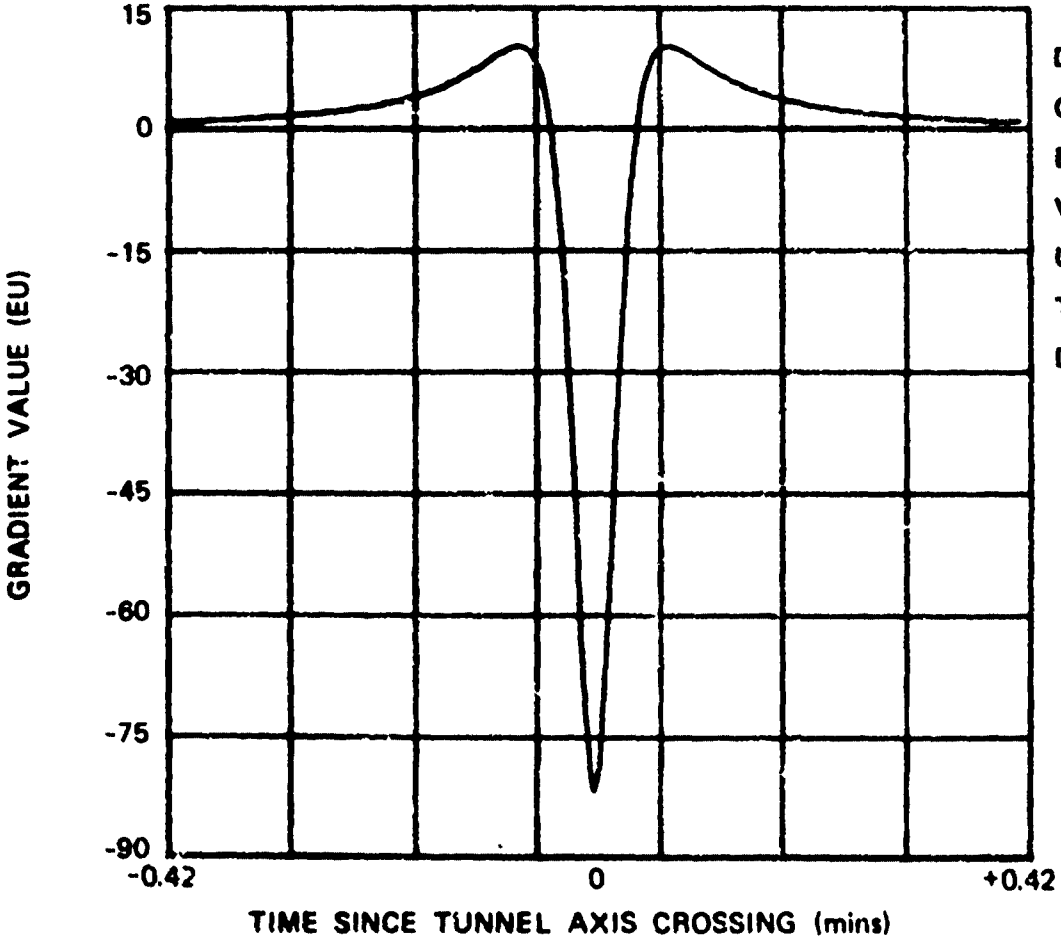
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23942



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda u}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.8 g/cm^3

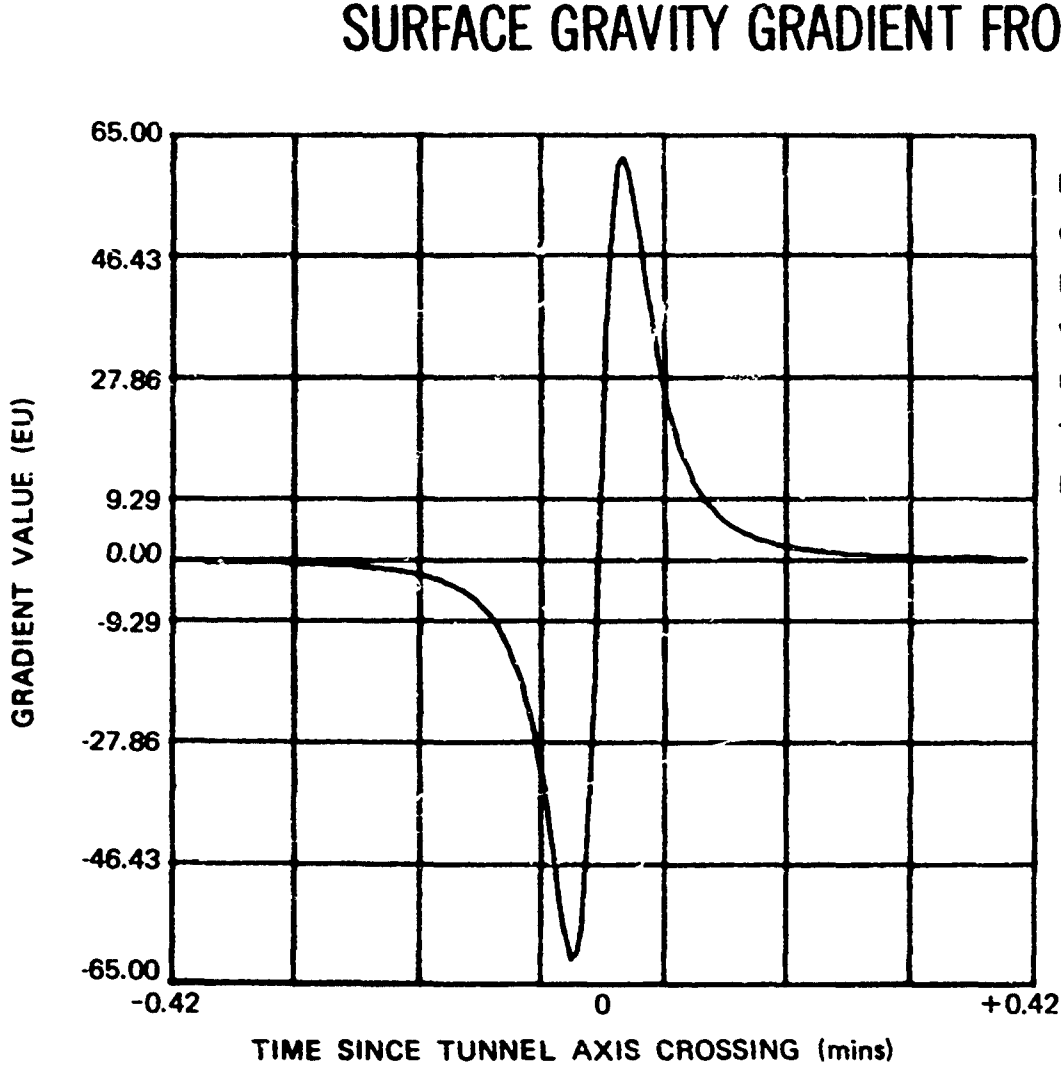
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23966

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{yu}

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

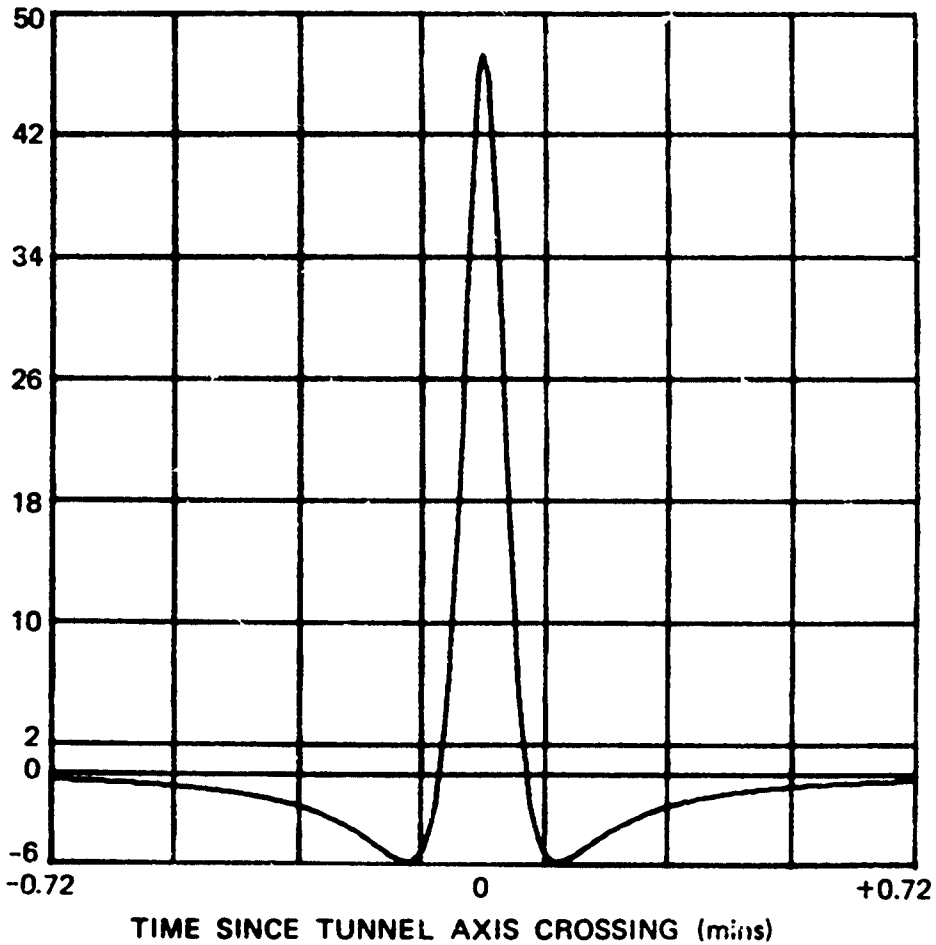
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 6 METERS
60° ENCOUNTER ANGLE

R-23940

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

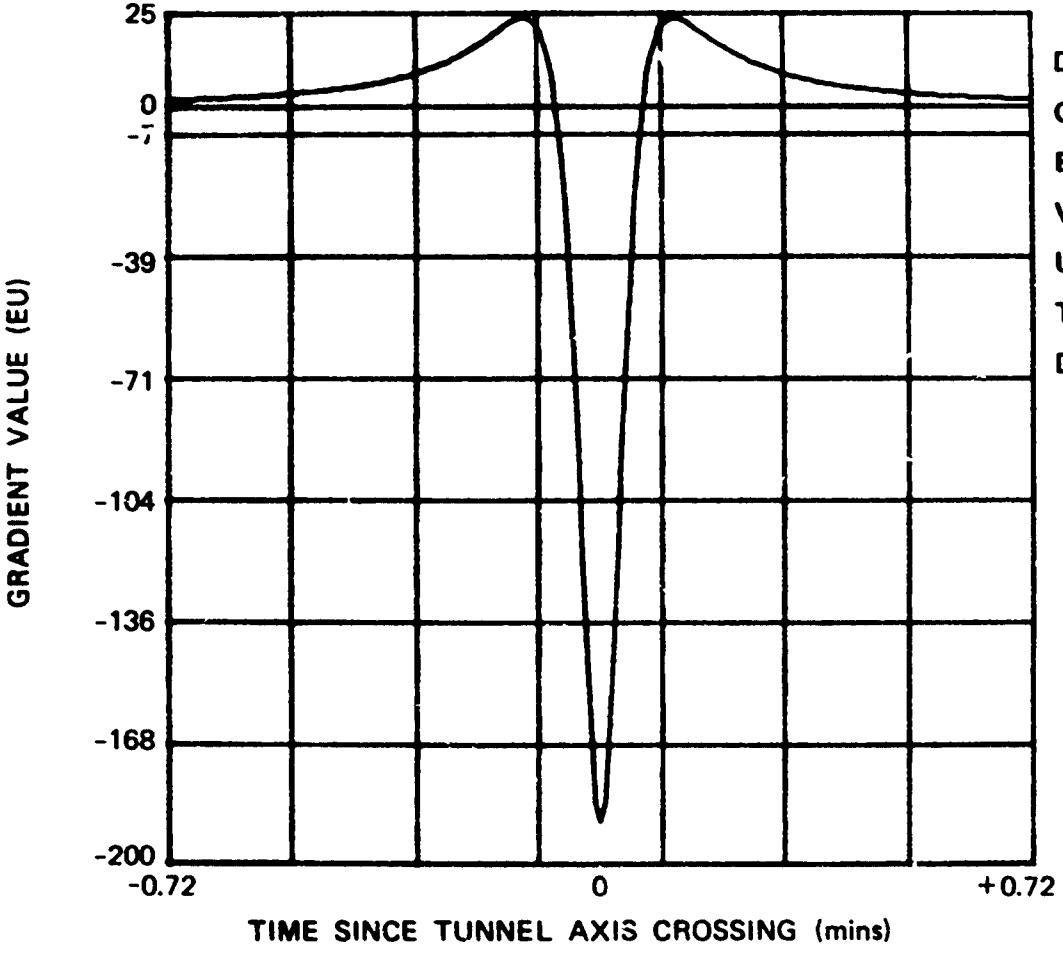
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23939



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

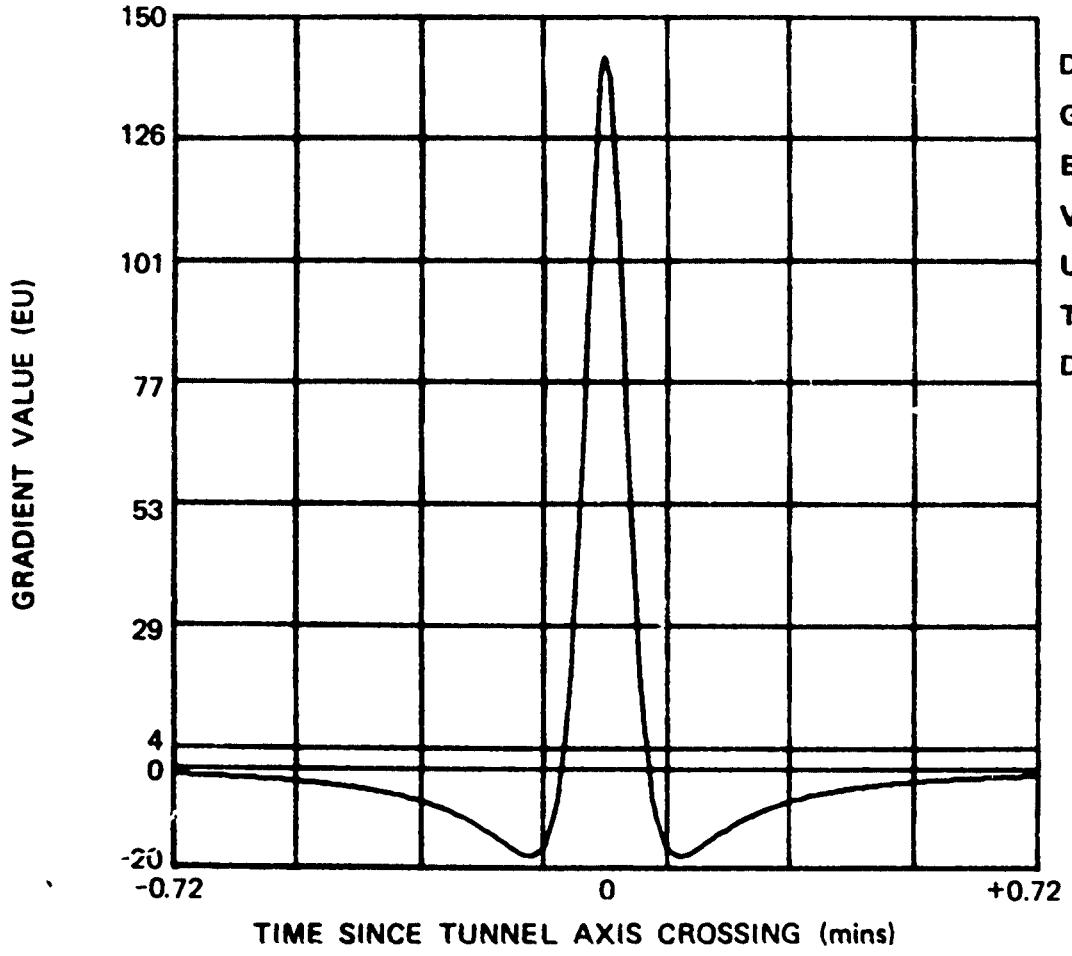
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23933



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{uu}

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

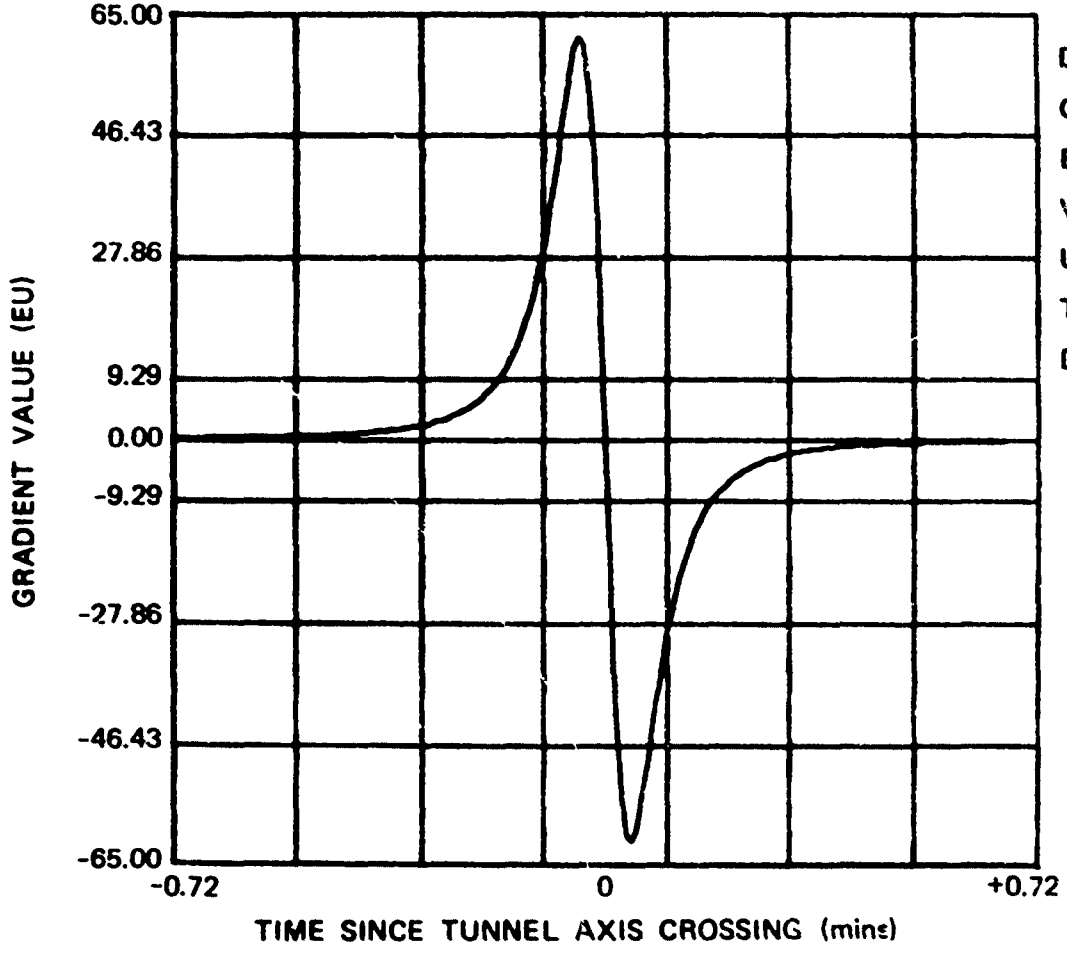
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23957

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

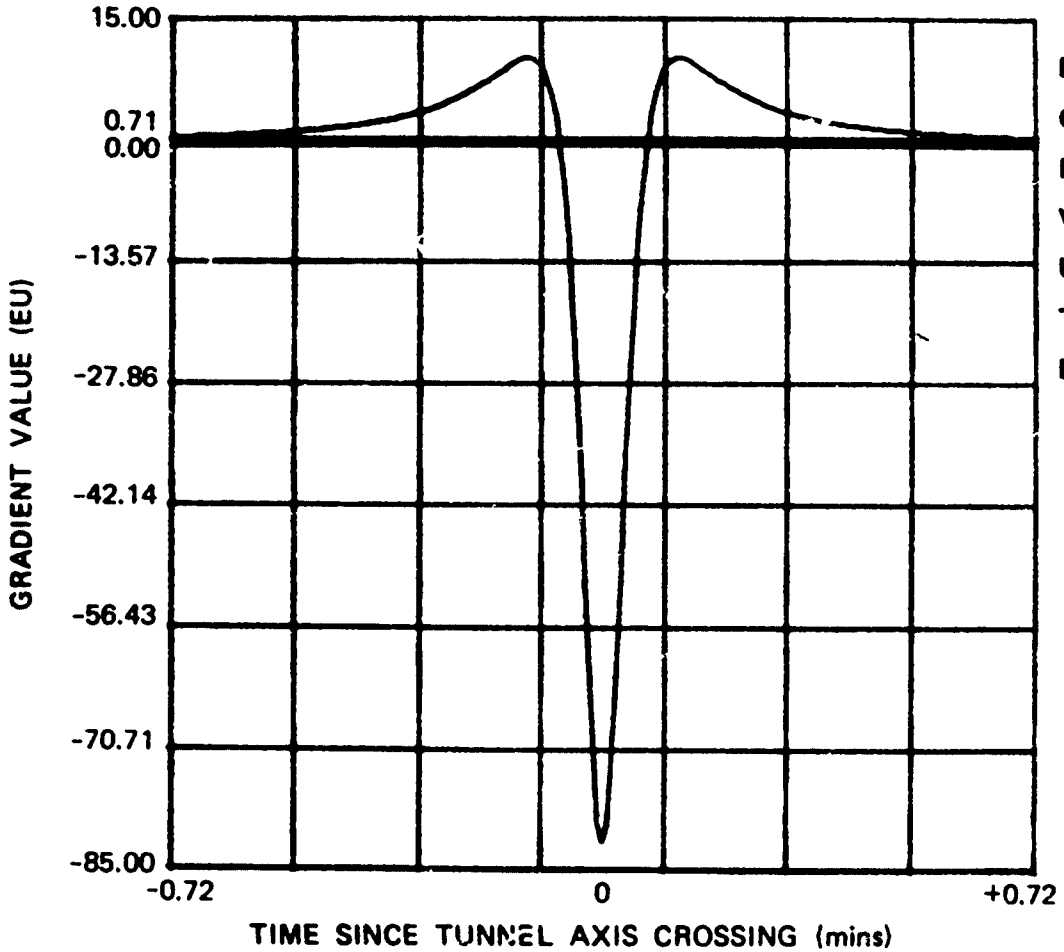
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23954

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

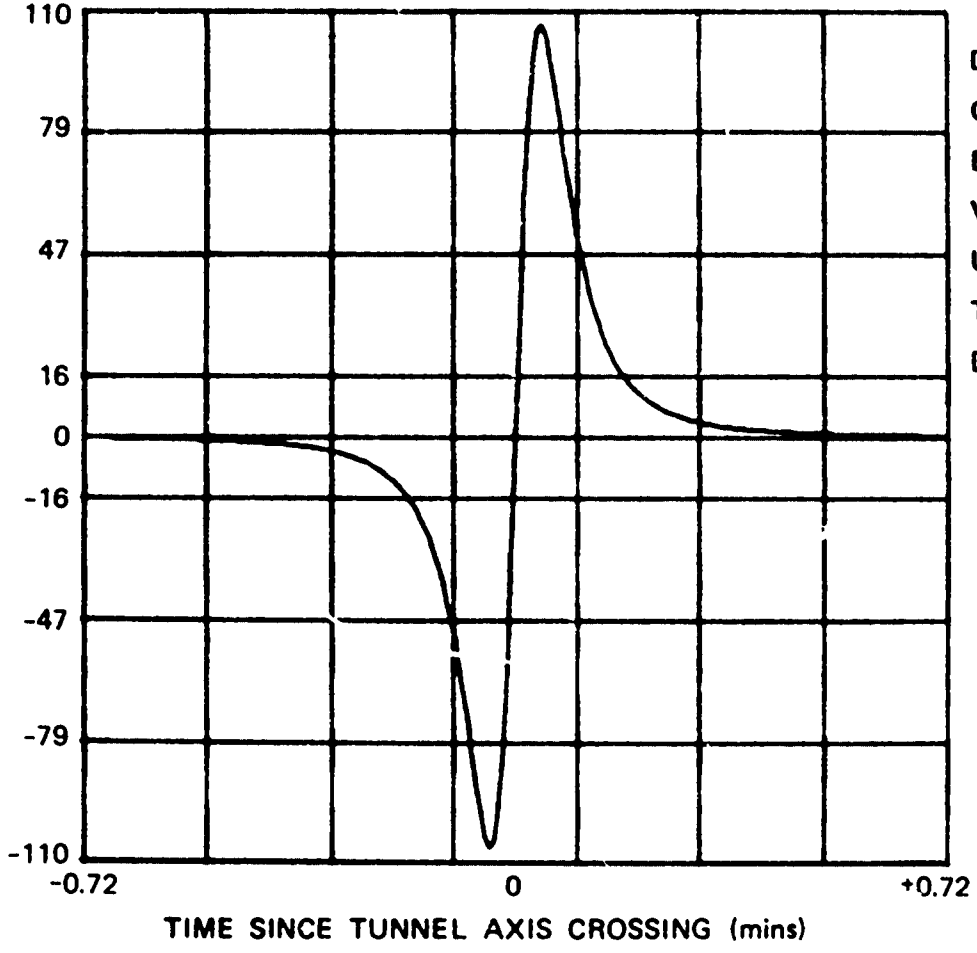
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23946

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 6m

GRAVITY GRADIENT ELEMENT = γ_{yu}

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

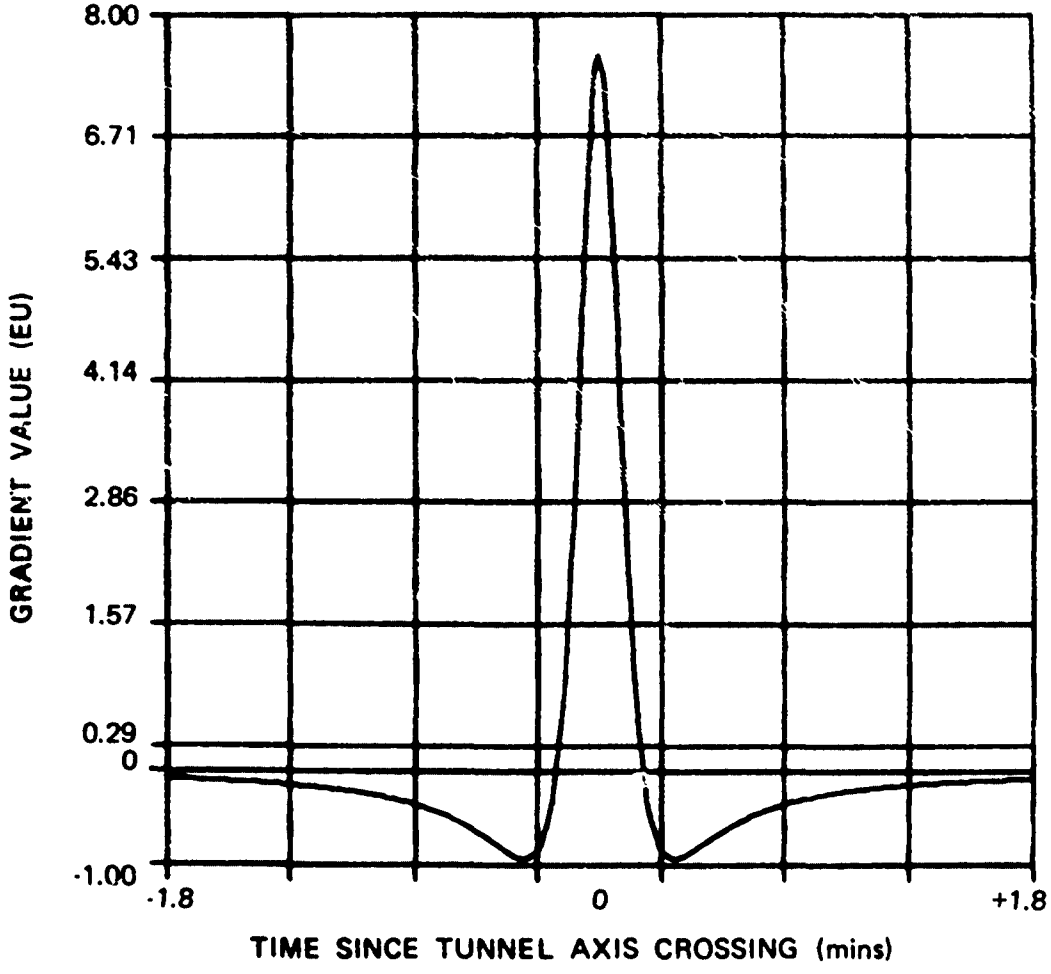
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 30 METERS
0° ENCOUNTER ANGLE

R-23928

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

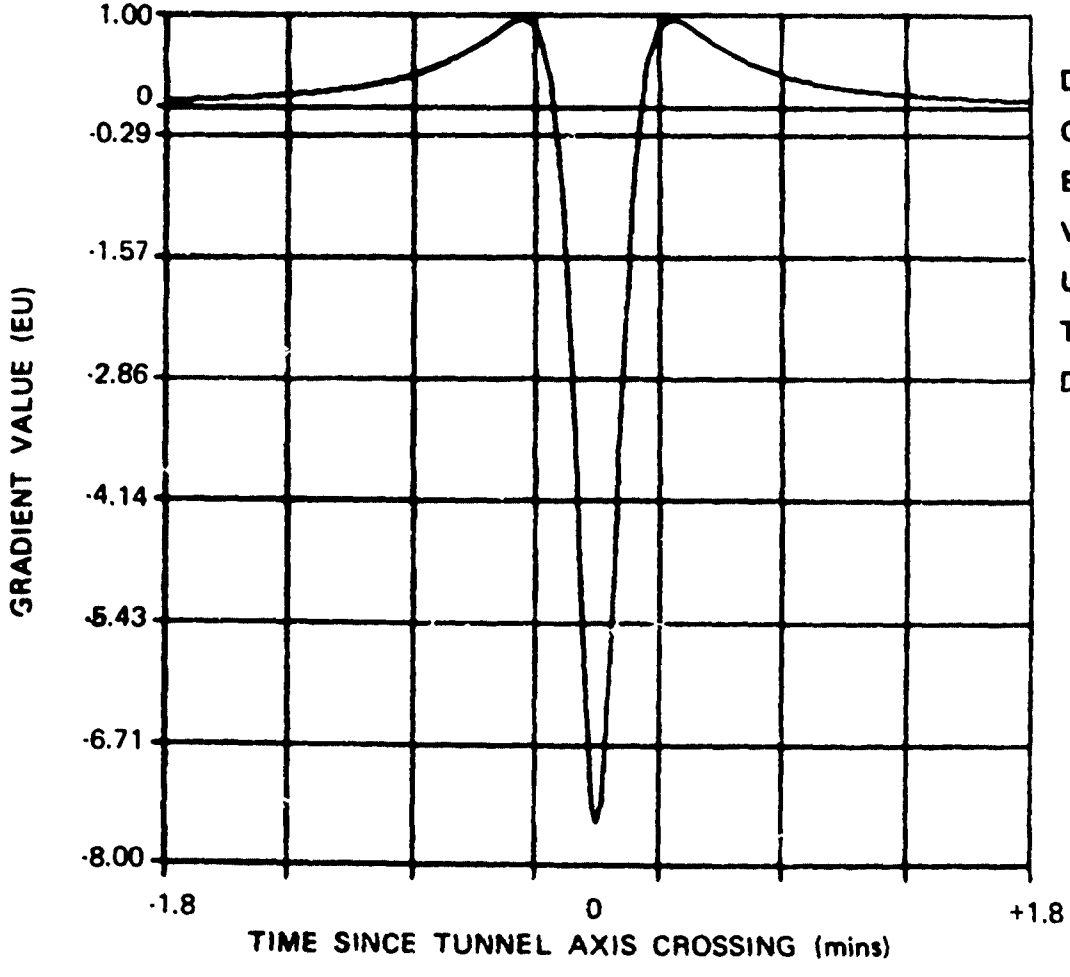
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23931



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

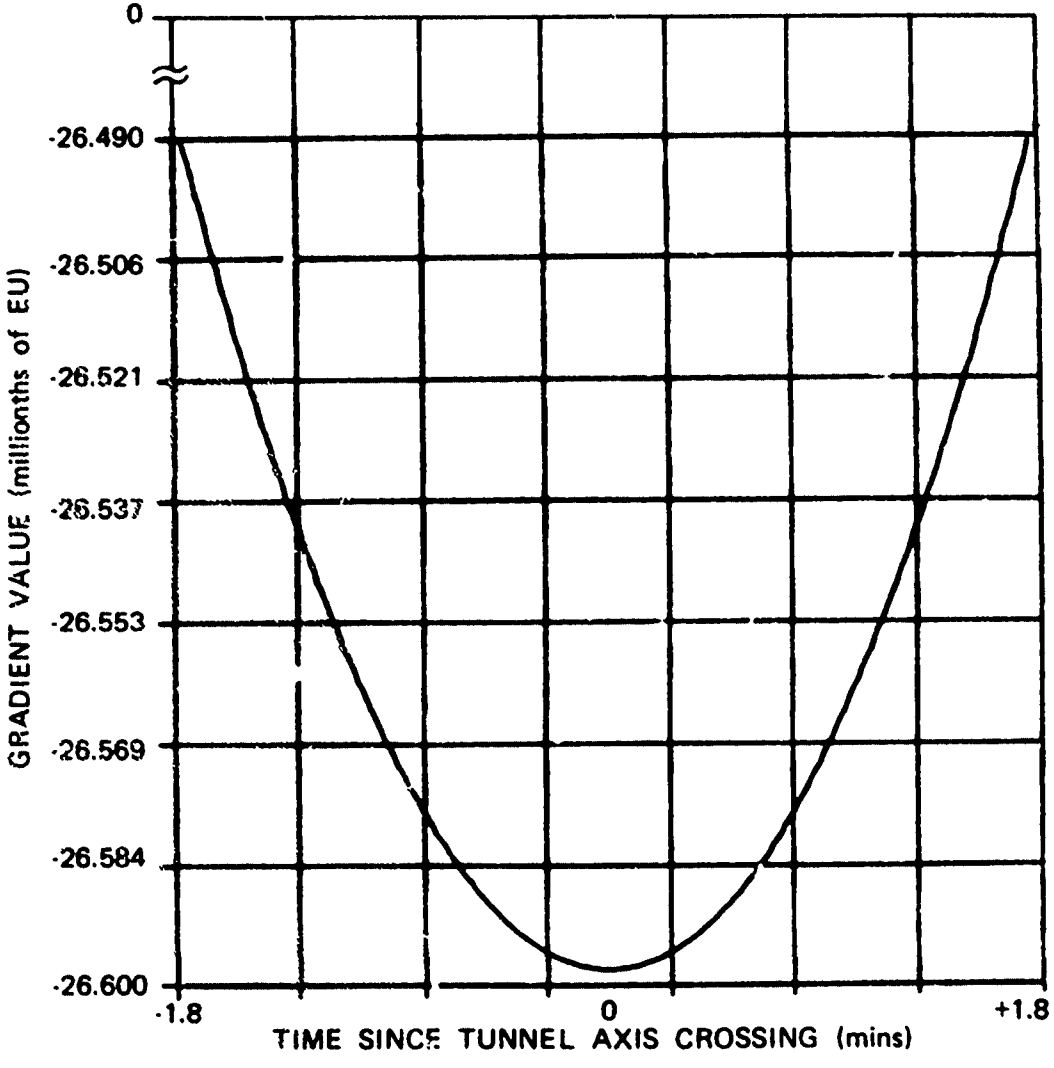
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23950

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

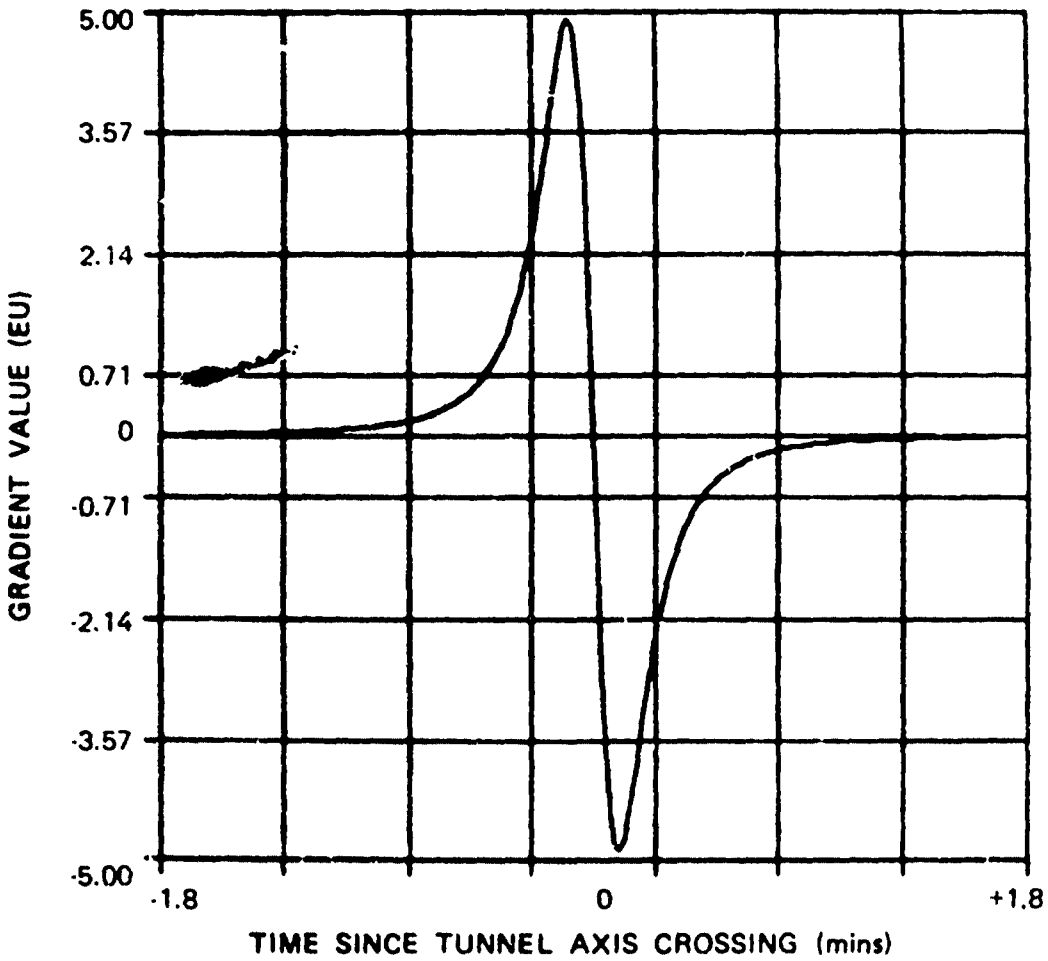
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23932

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 0^{o}

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

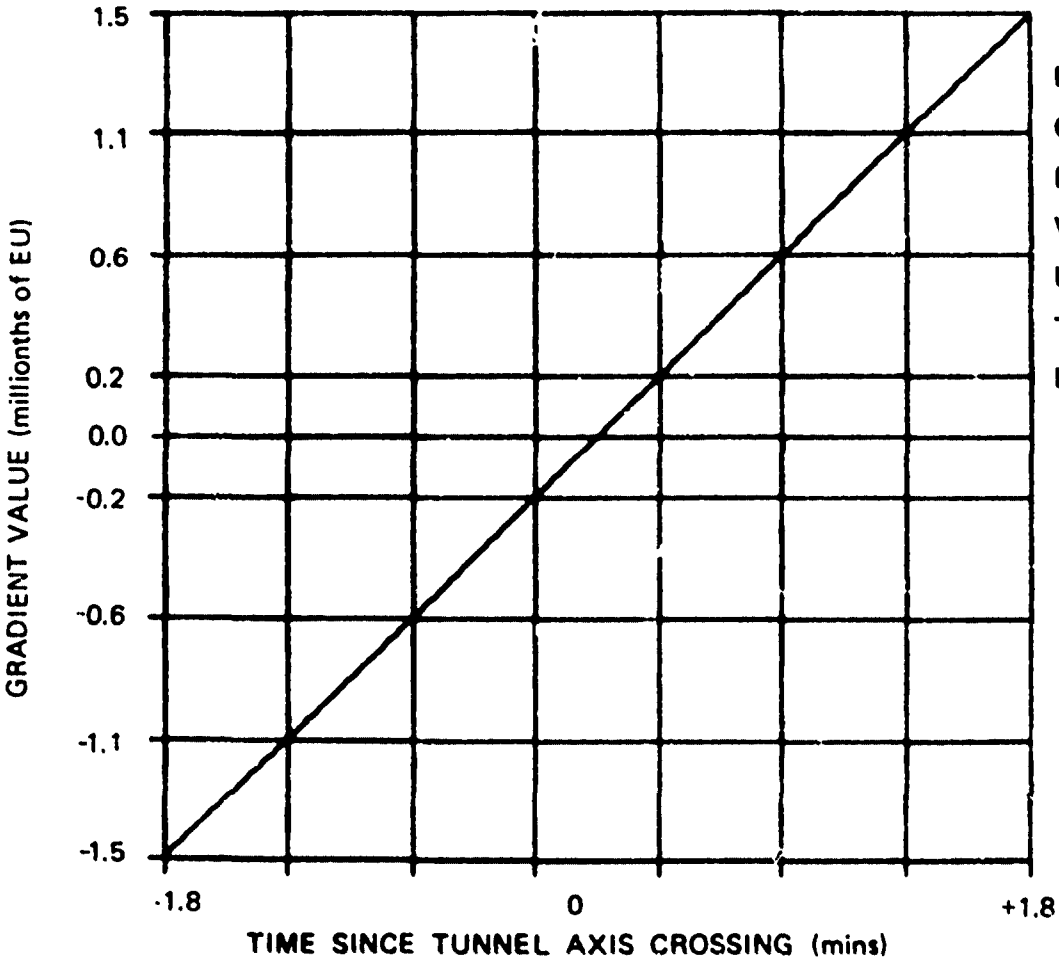
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23934



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda u}$

ENCOUNTER ANGLE (θ) = 0^{o}

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

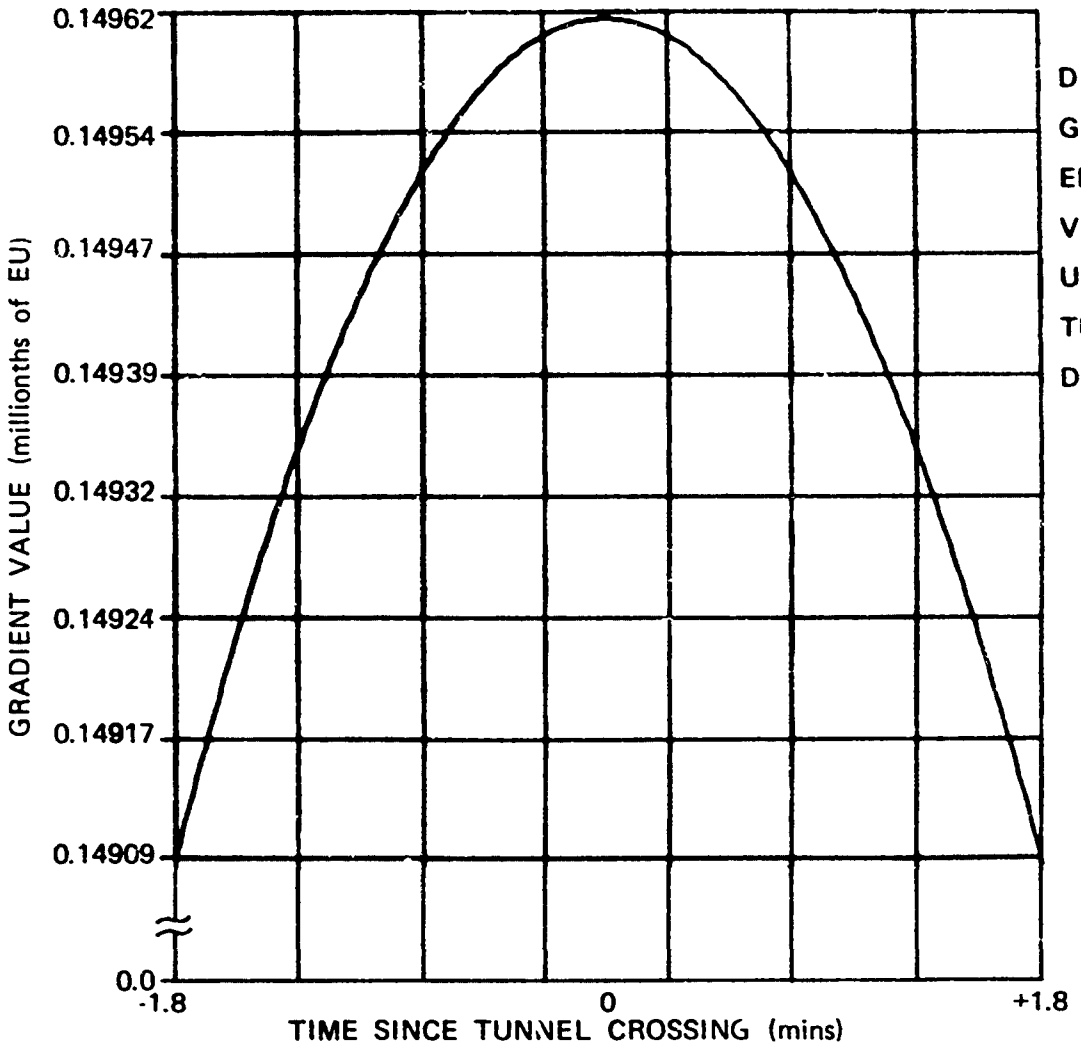
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23949

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = γ_{yu}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

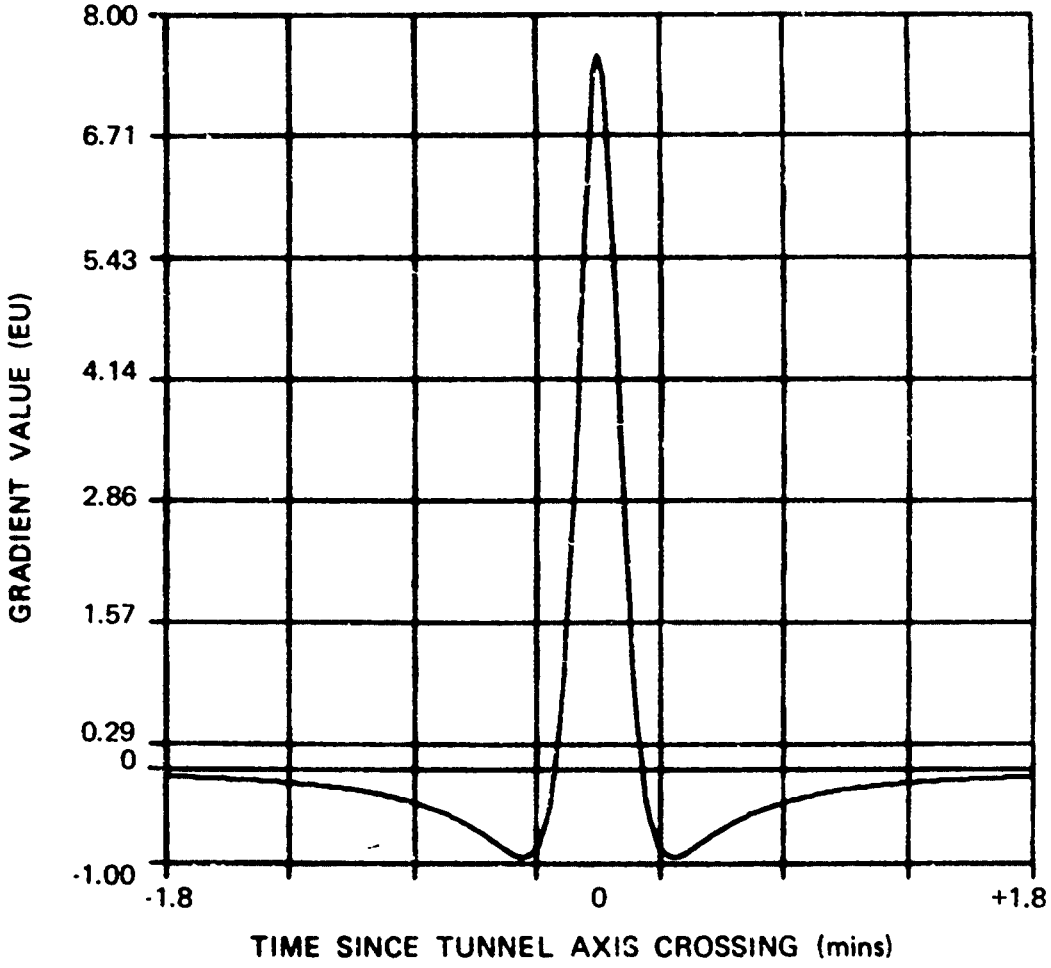
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 30 METERS
0° ENCOUNTER ANGLE

R-23928

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

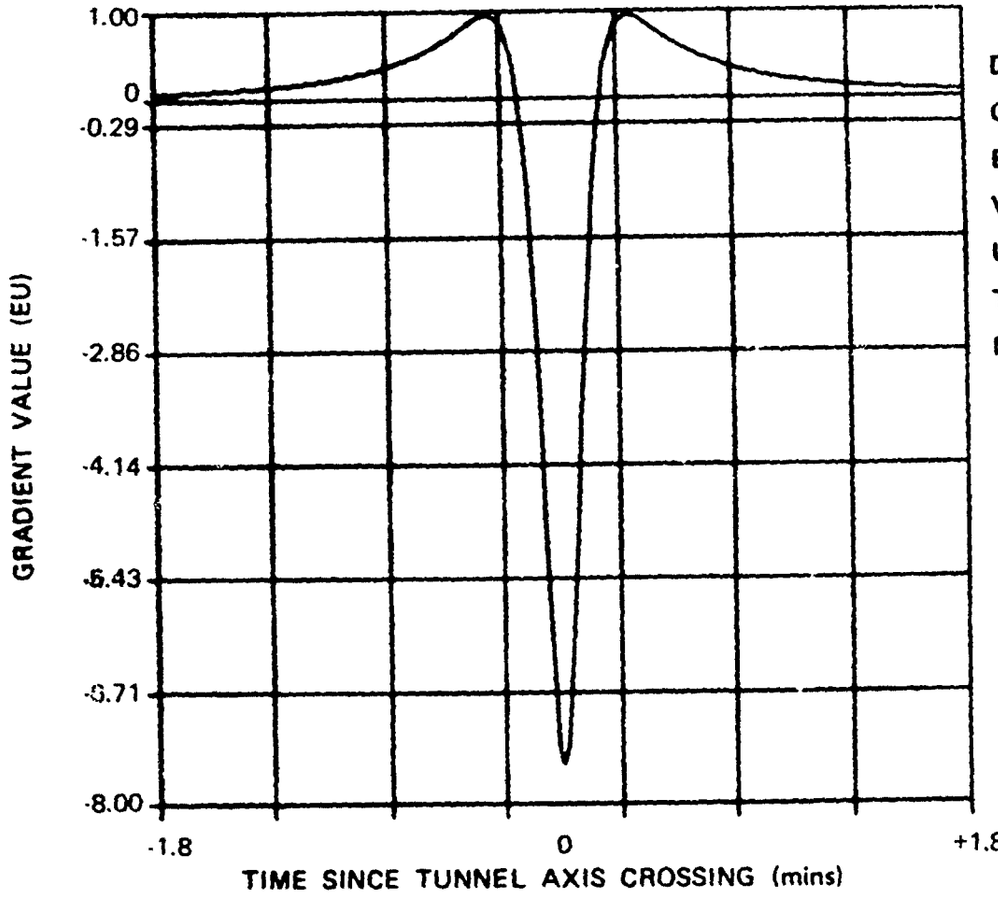
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23931



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

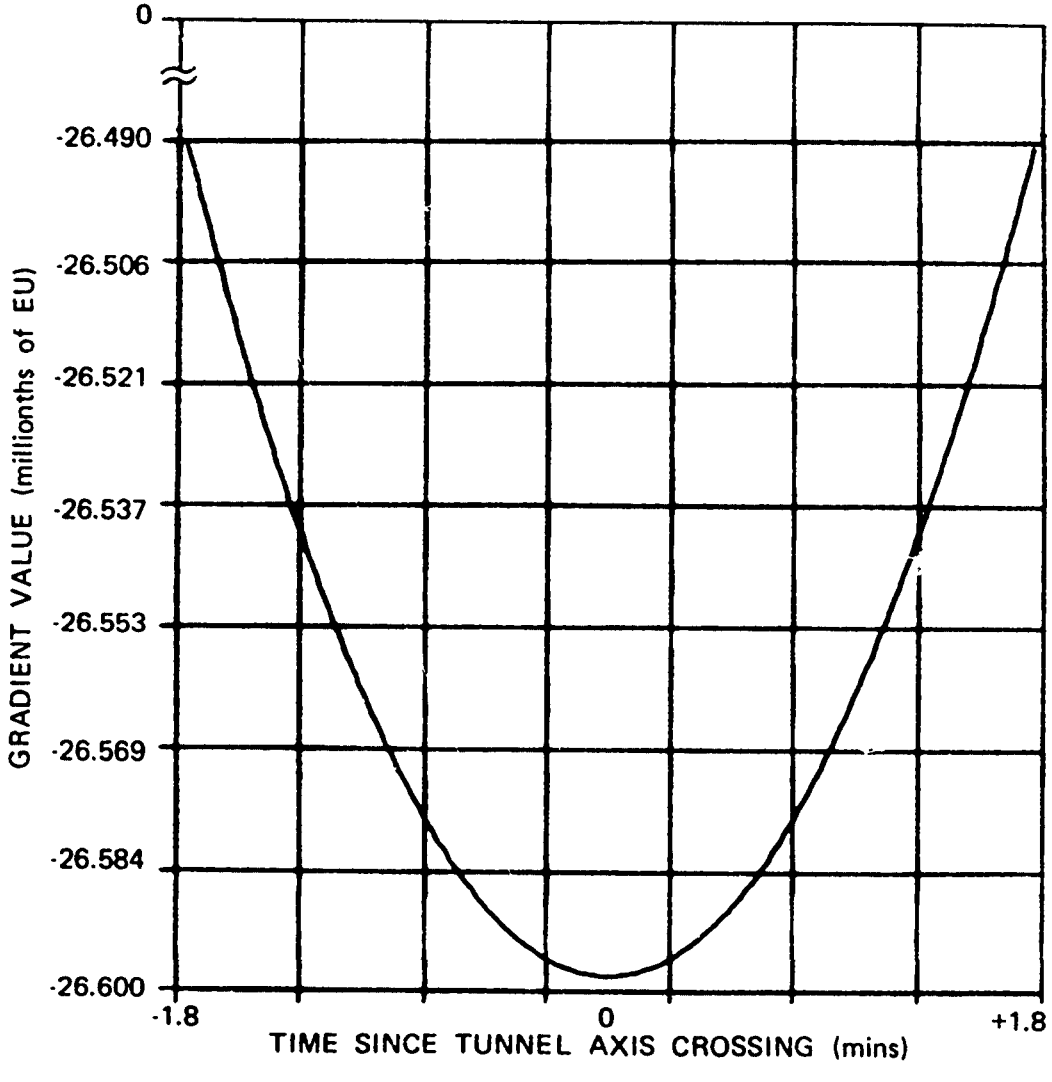
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23950

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

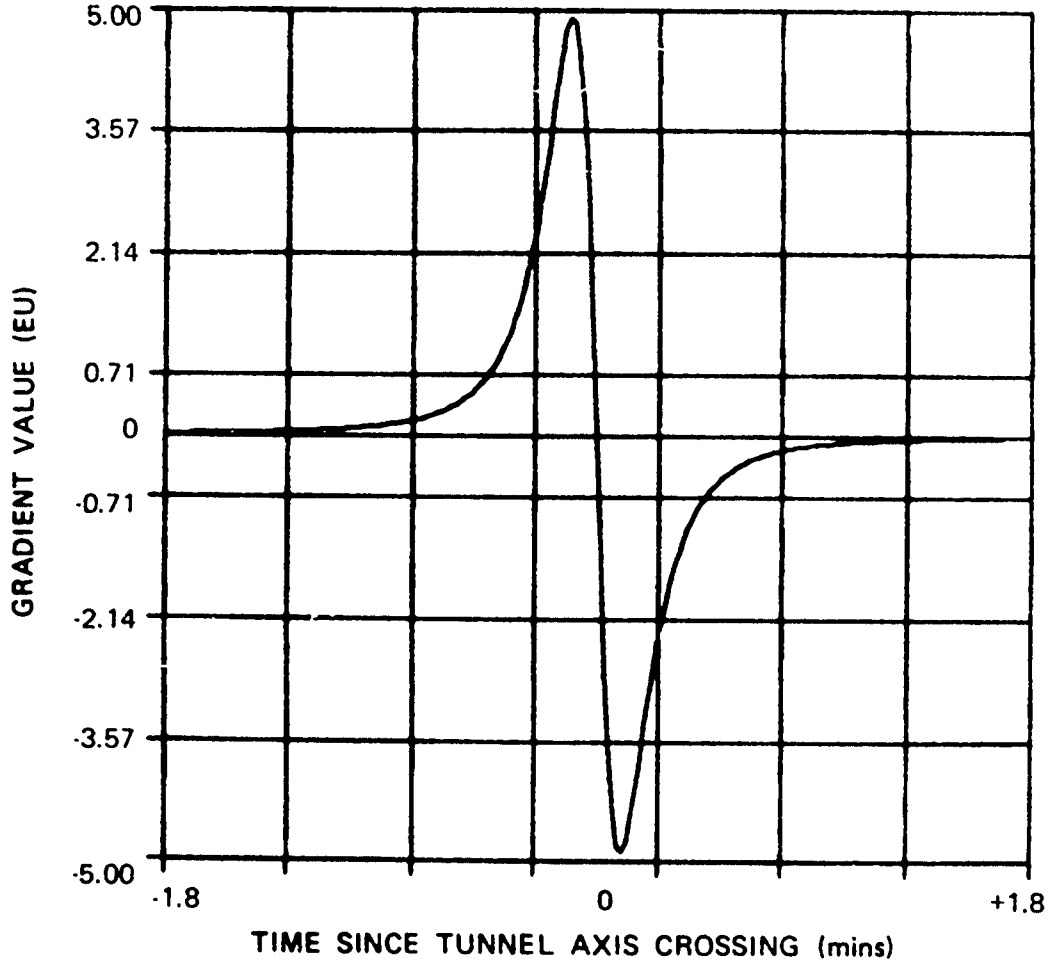
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23932

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 0^{o}

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

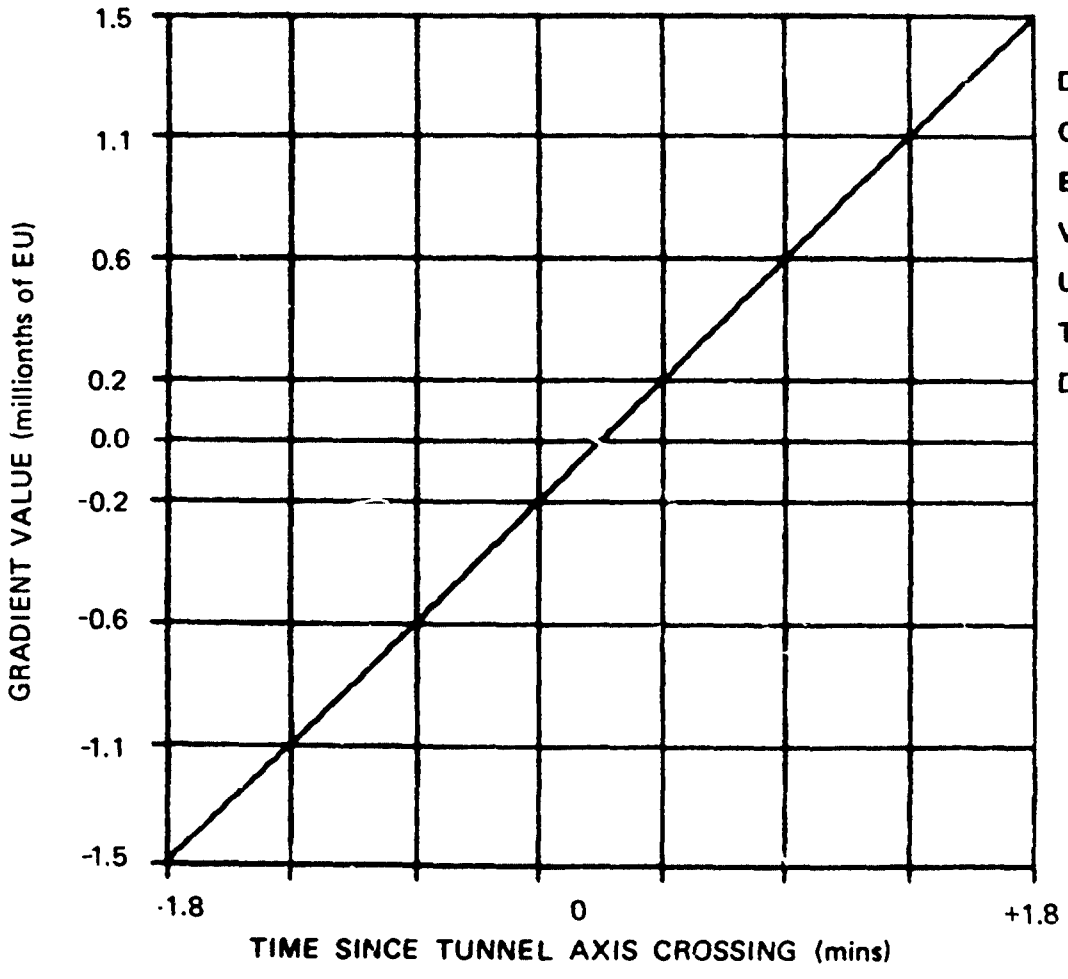
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23934



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda u}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

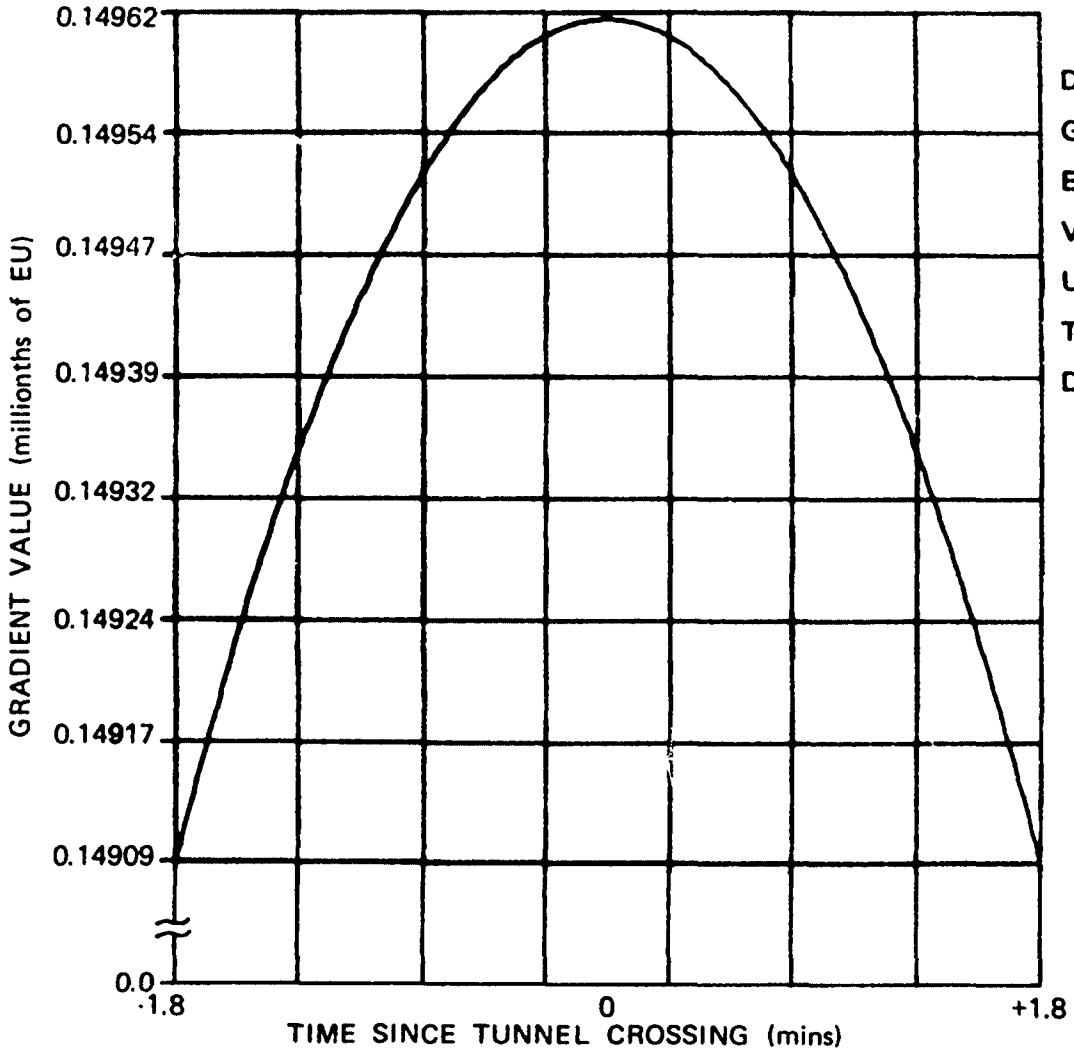
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23949

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = γ_{yu}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

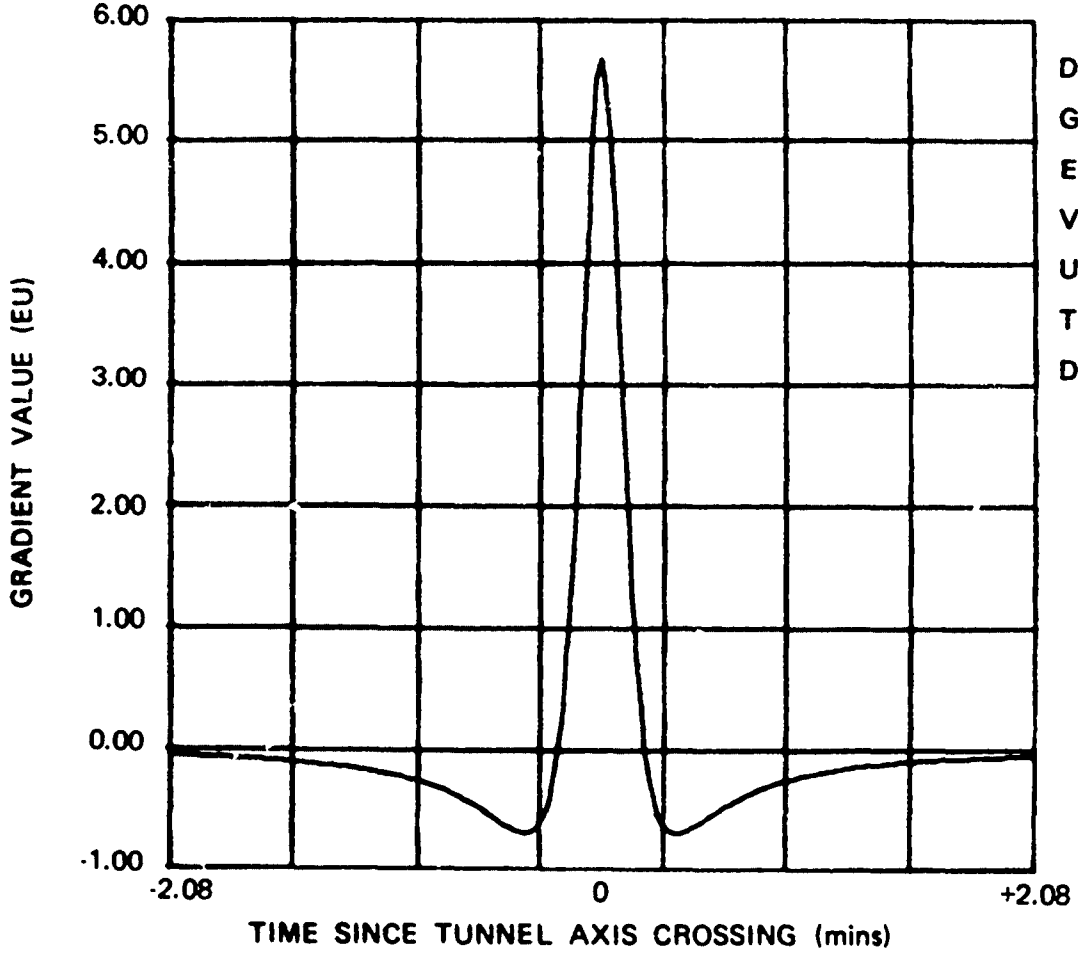
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 30 METERS
30° ENCOUNTER ANGLE

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23967



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (ρ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

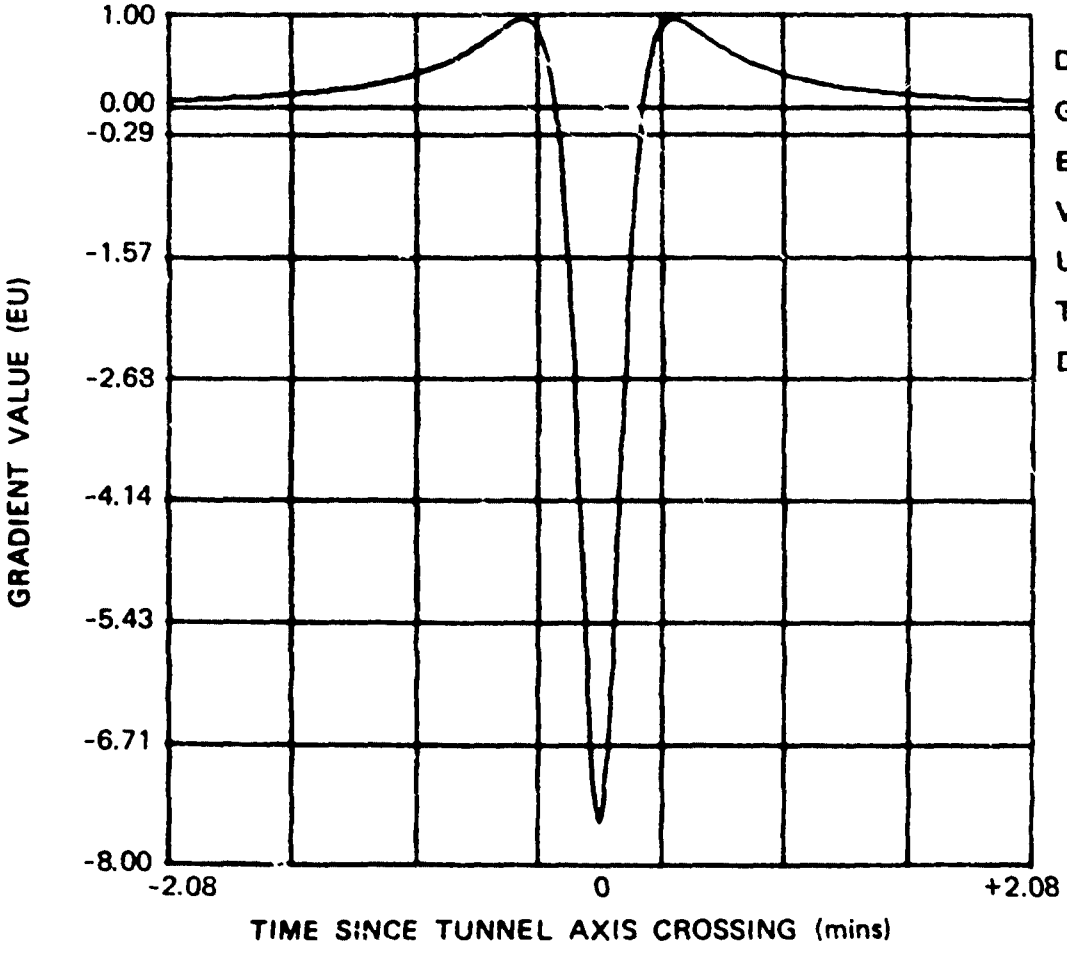
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23975

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

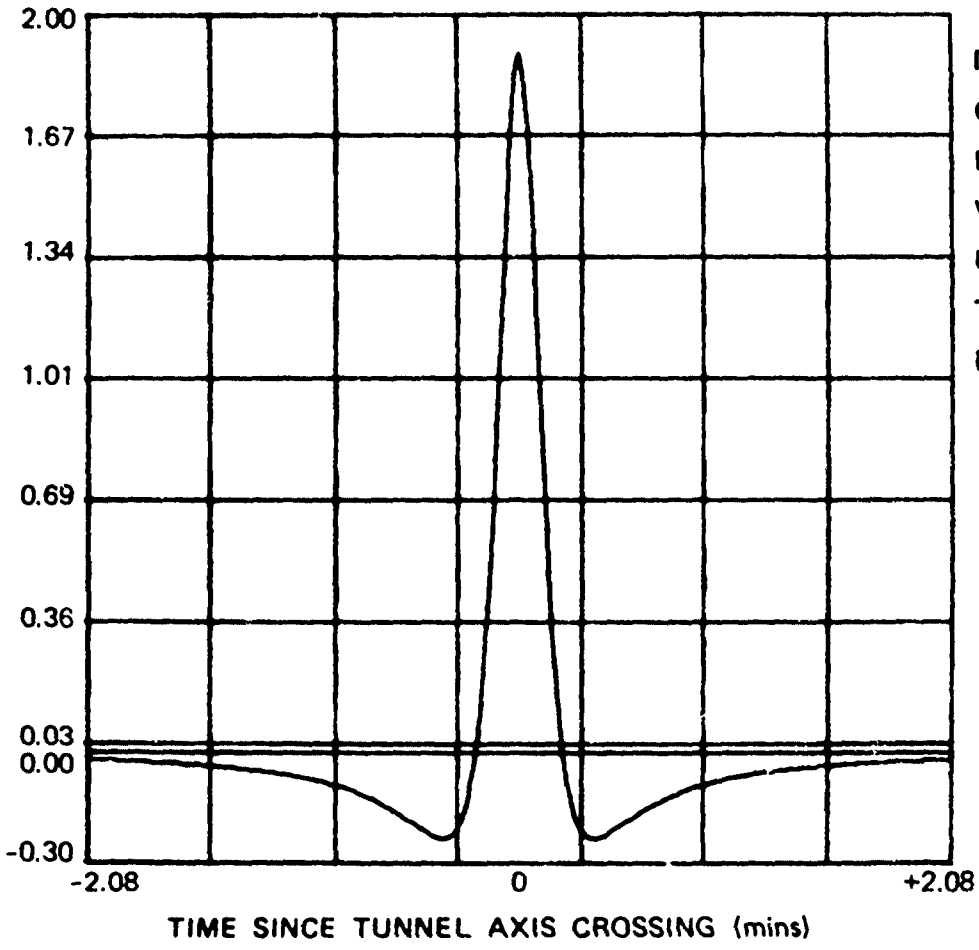
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23973

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

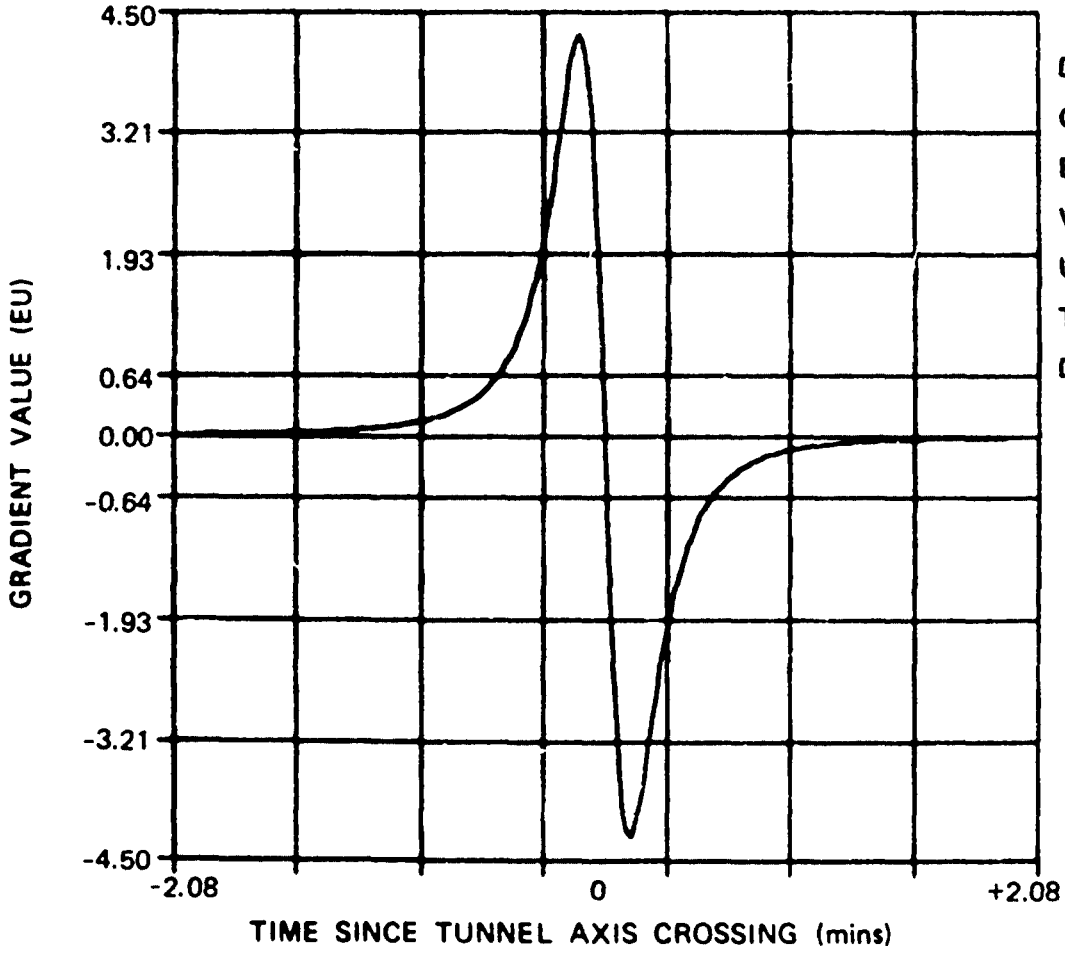
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23971

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

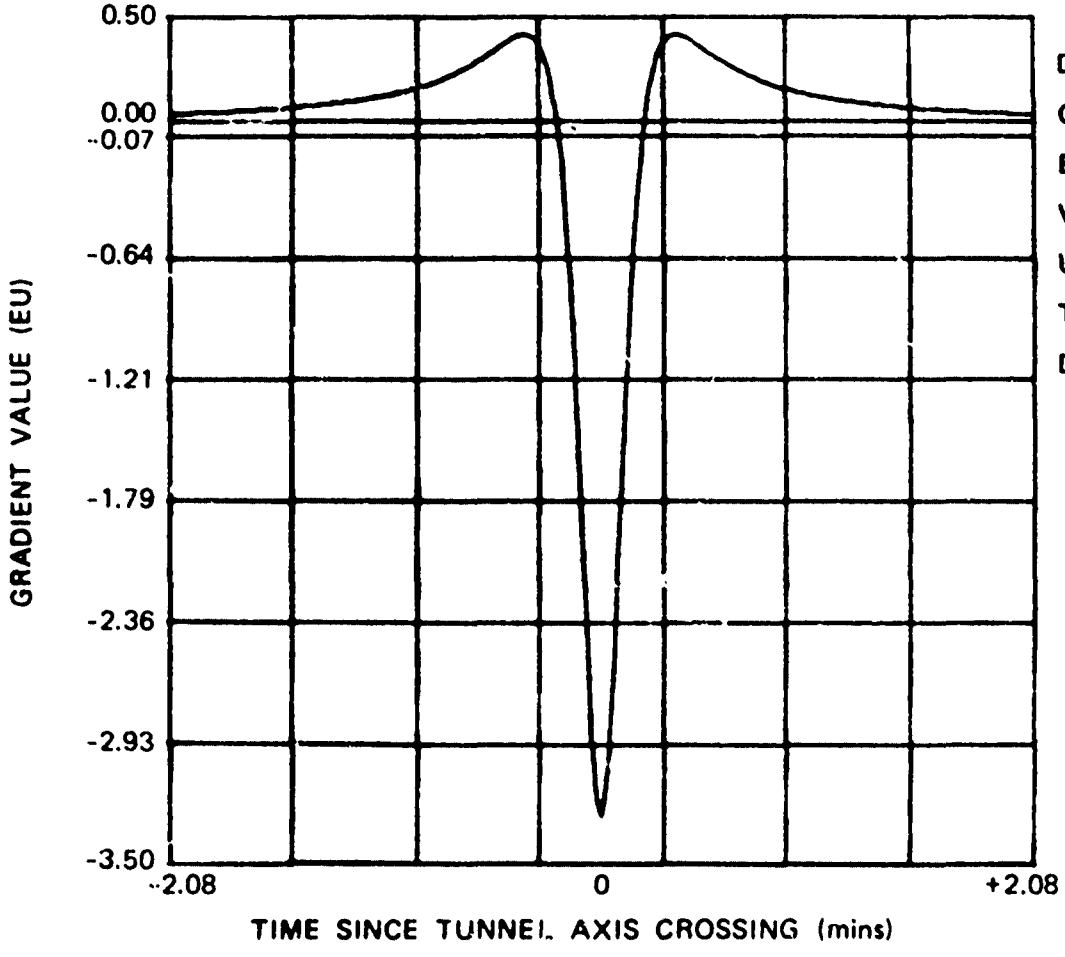
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23970



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

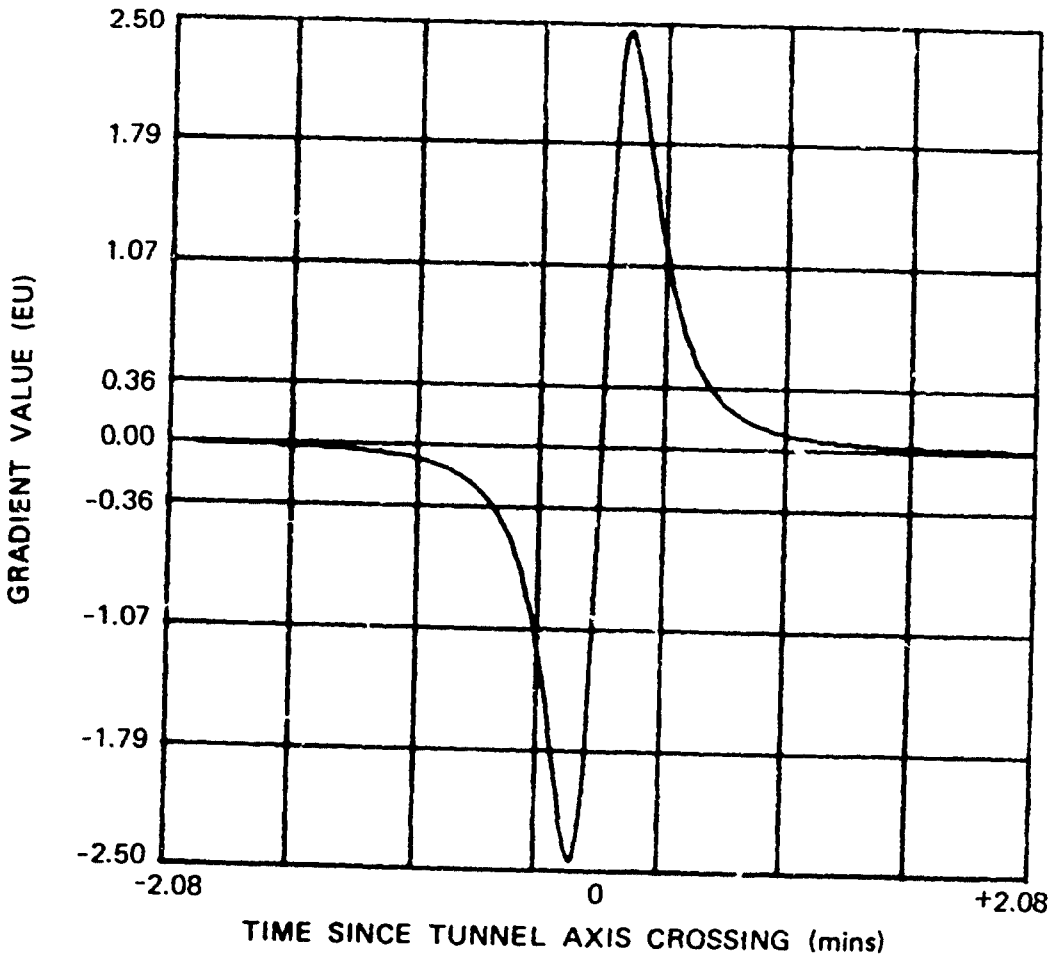
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23955



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{y\mu}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

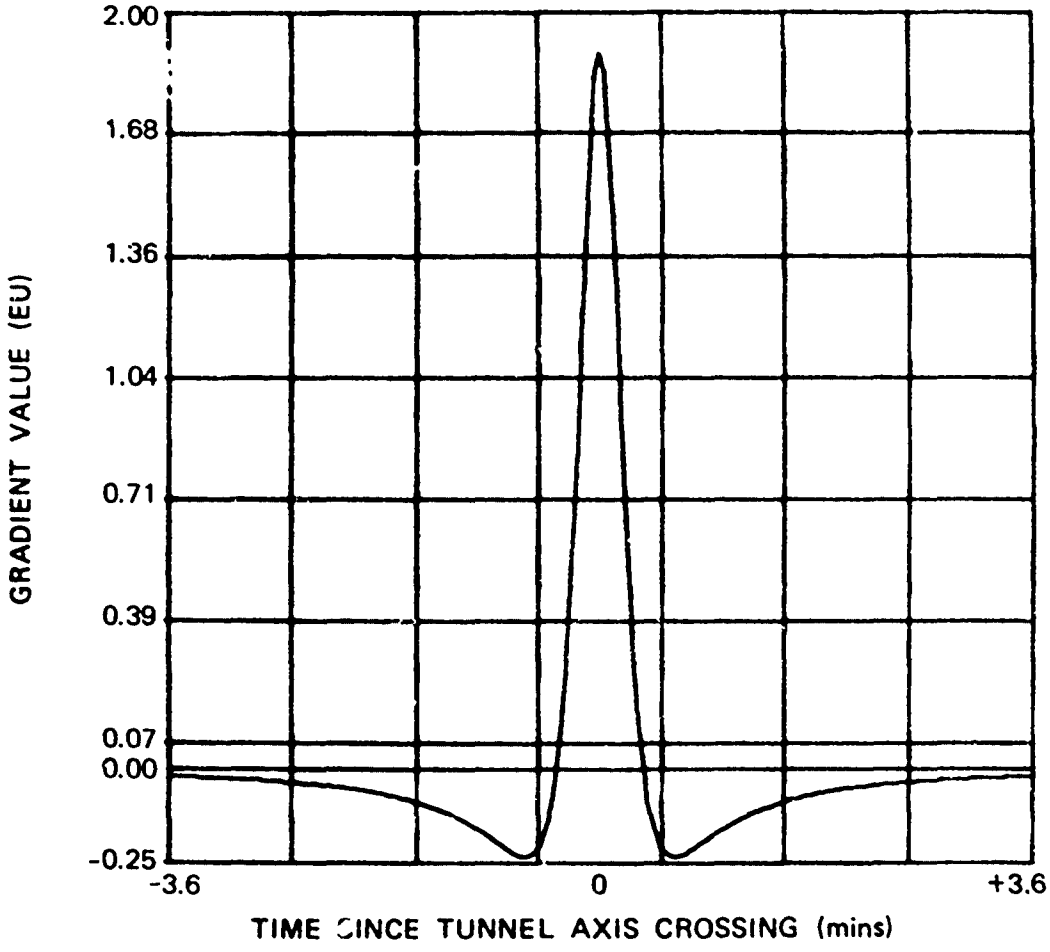
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 30 METERS
60° ENCOUNTER ANGLE

R-23956

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

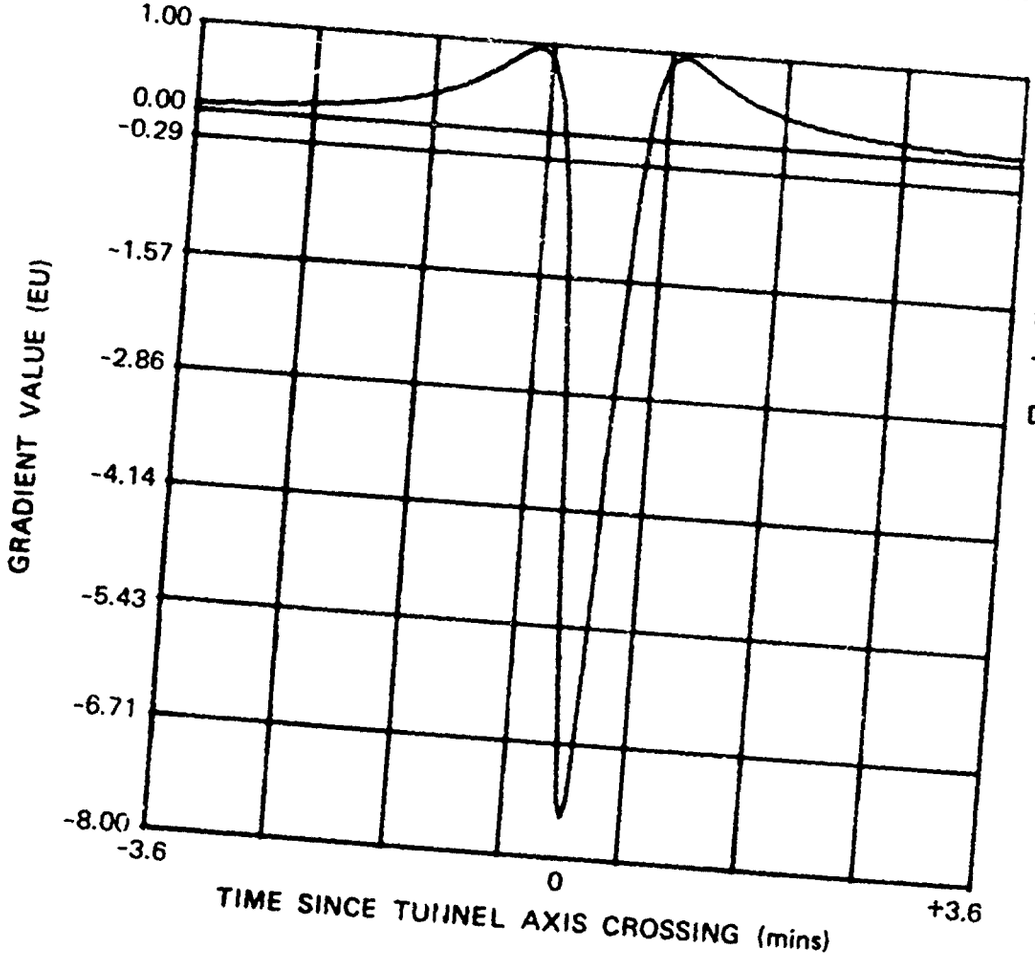
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23953



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

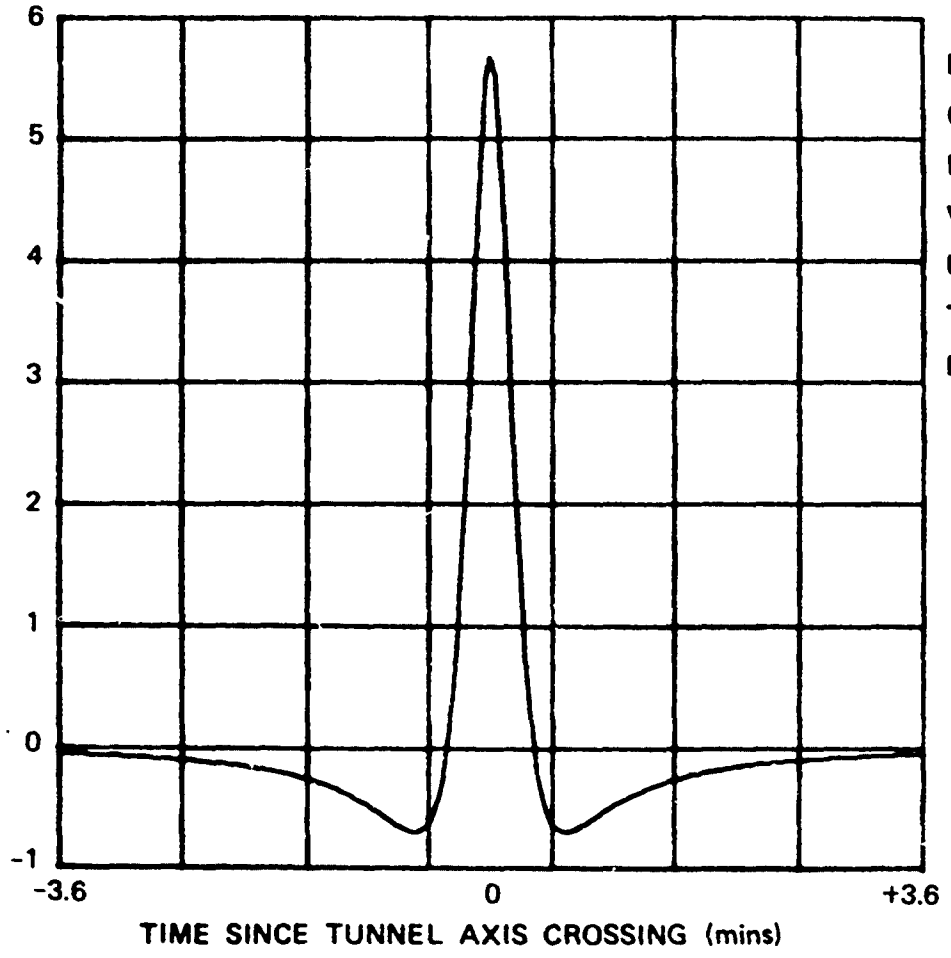
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23952



DEPTH TO TUNNEL AXIS = 30 m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

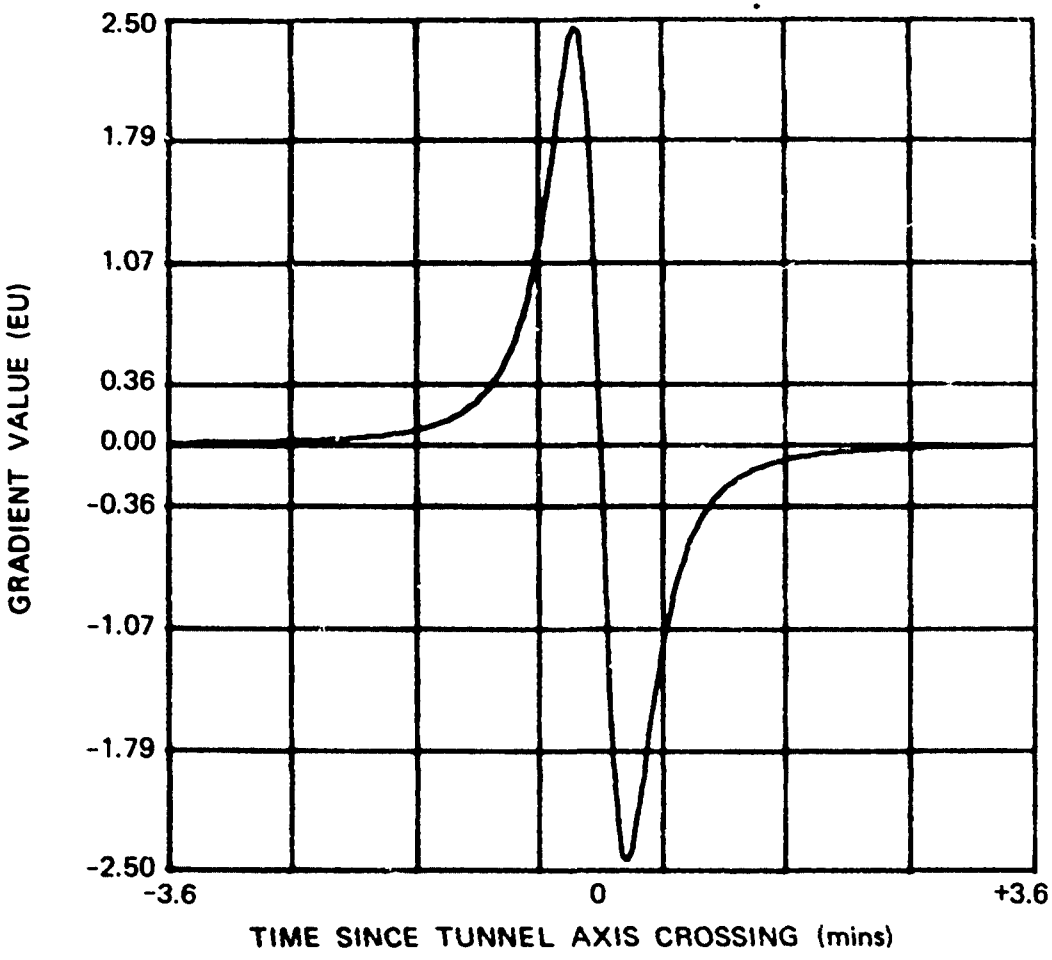
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23951



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

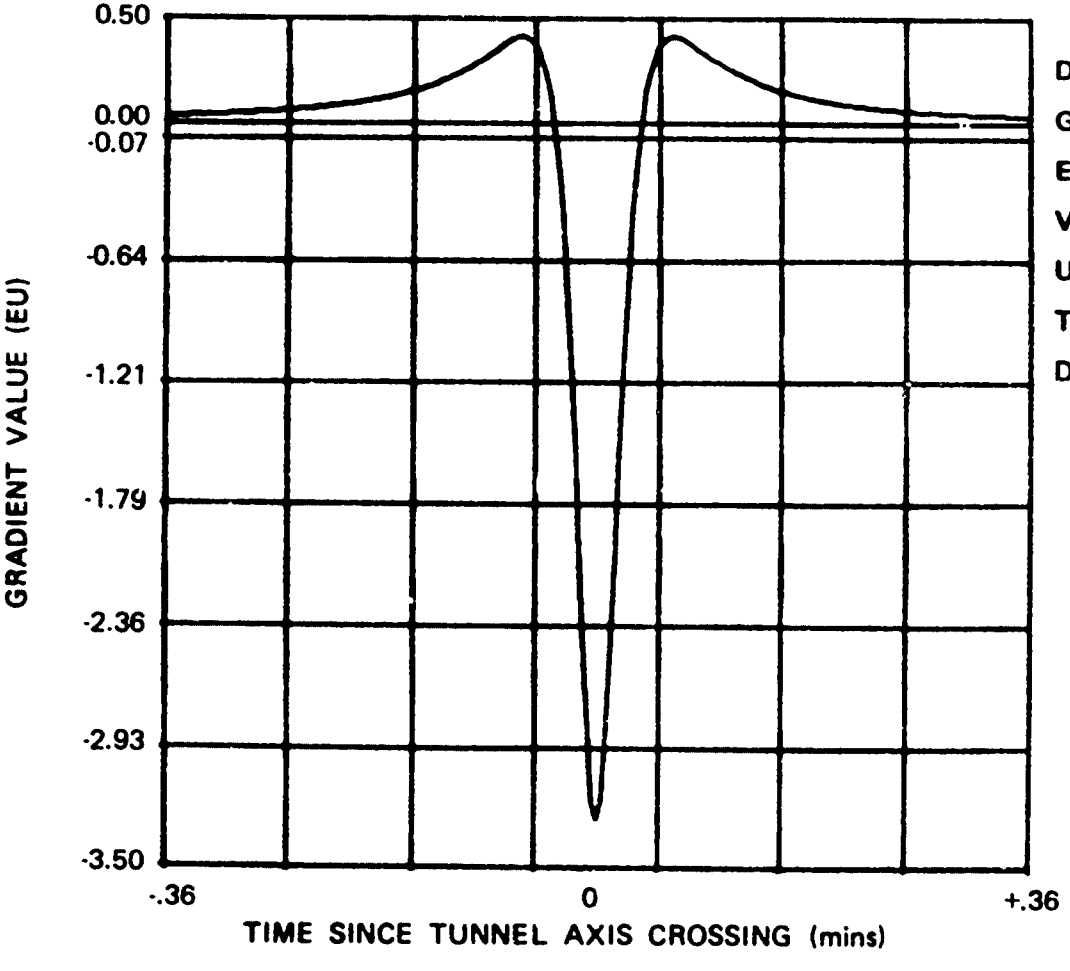
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23965



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

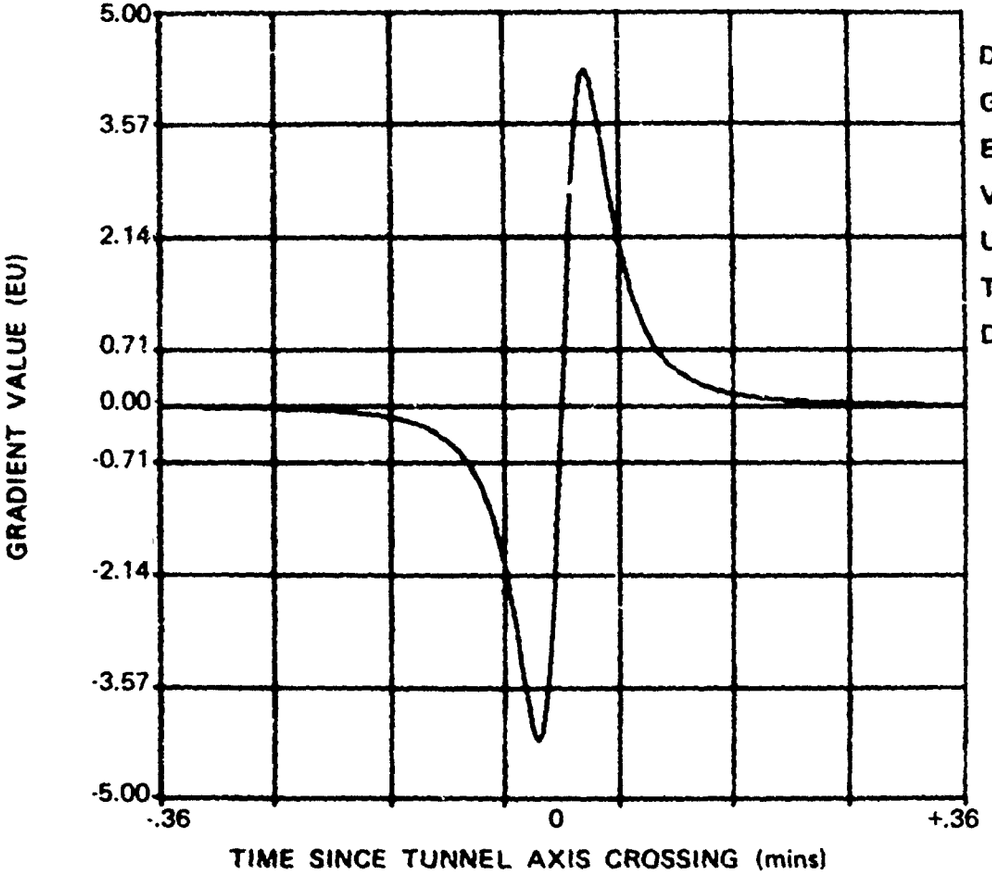
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23969

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 30m

GRAVITY GRADIENT ELEMENT = $\gamma_{y\mu}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

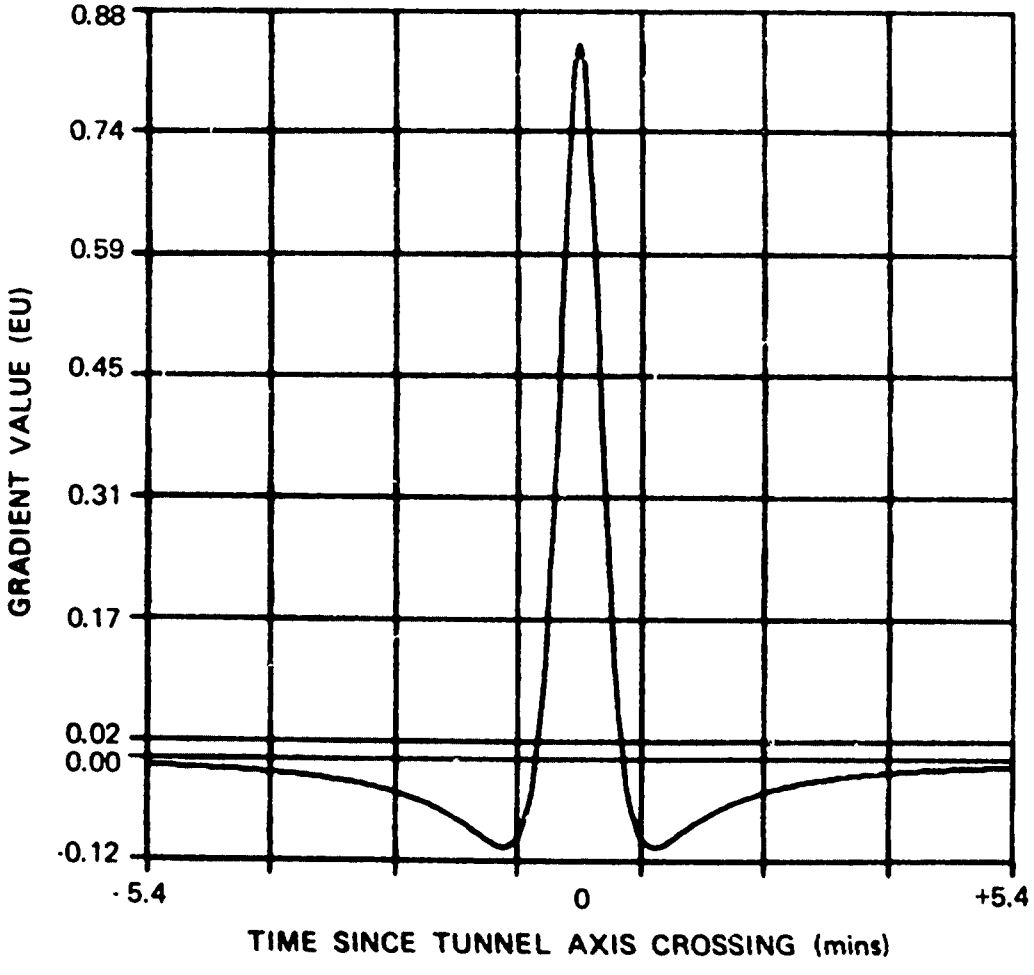
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 90 METERS
0° ENCOUNTER ANGLE

R-23963

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

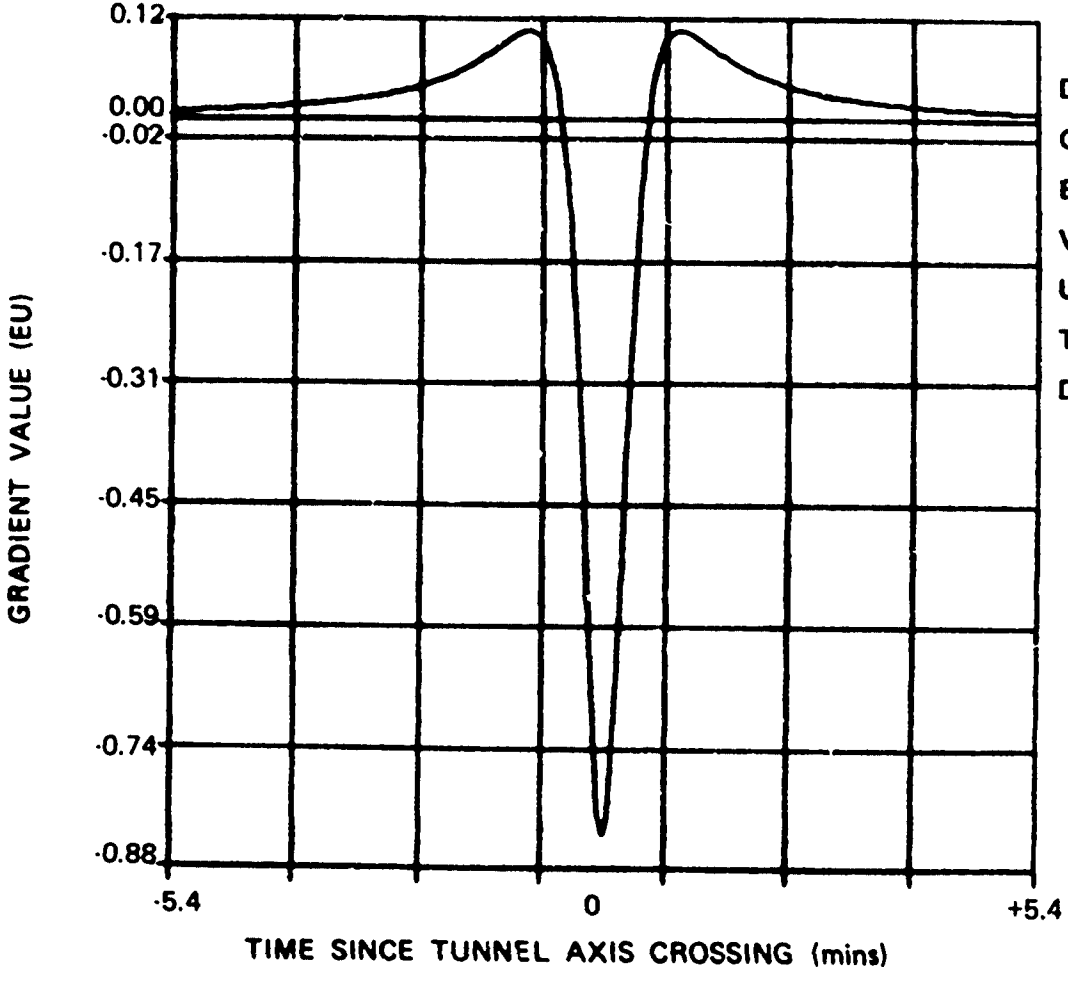
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23958



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

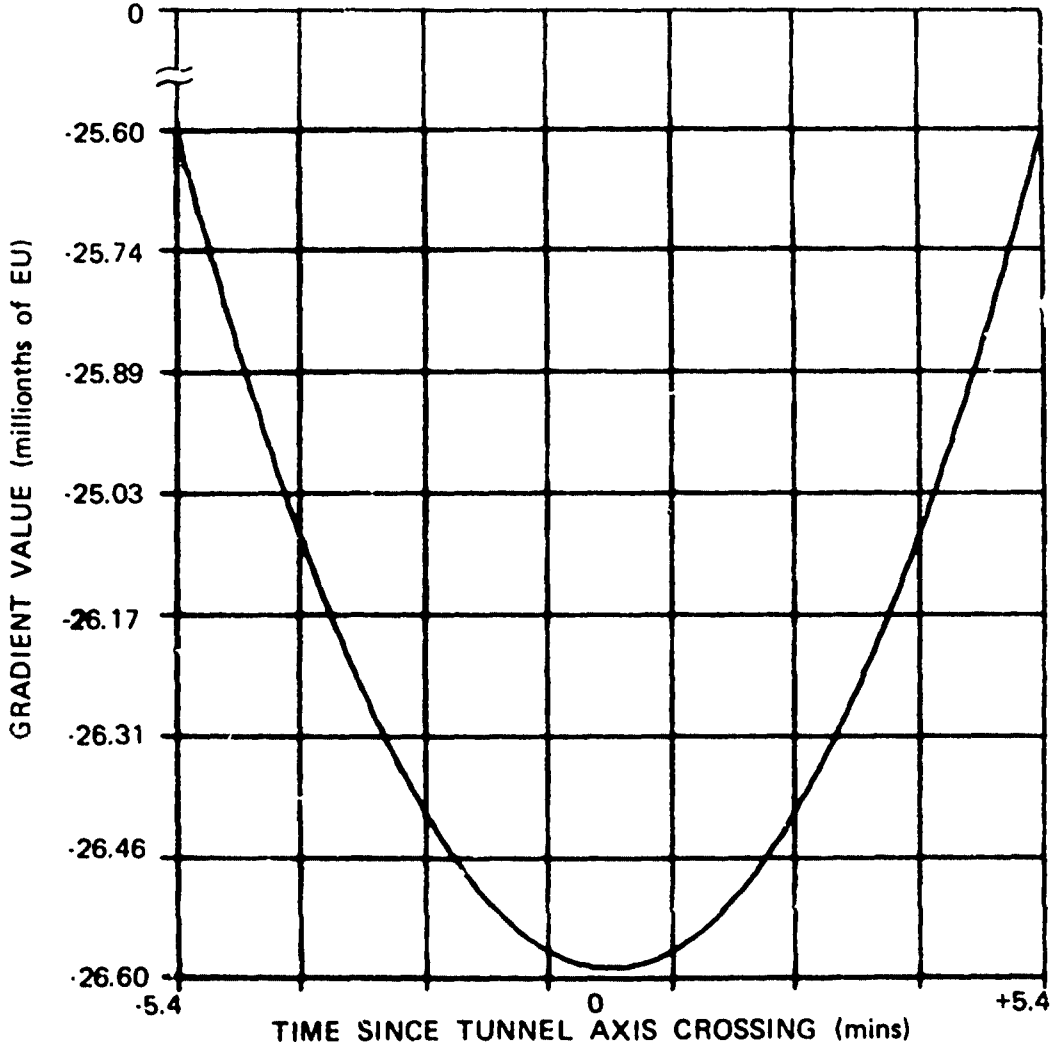
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23945



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

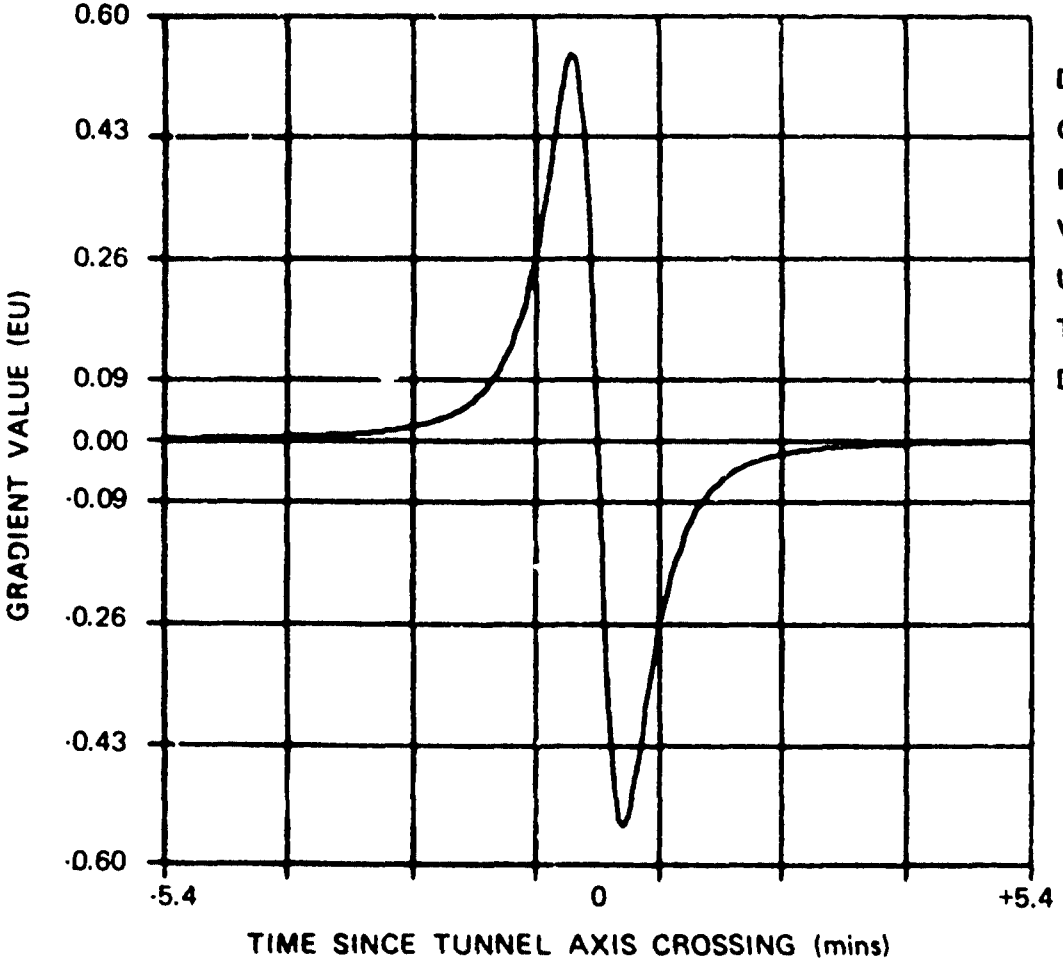
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23962

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

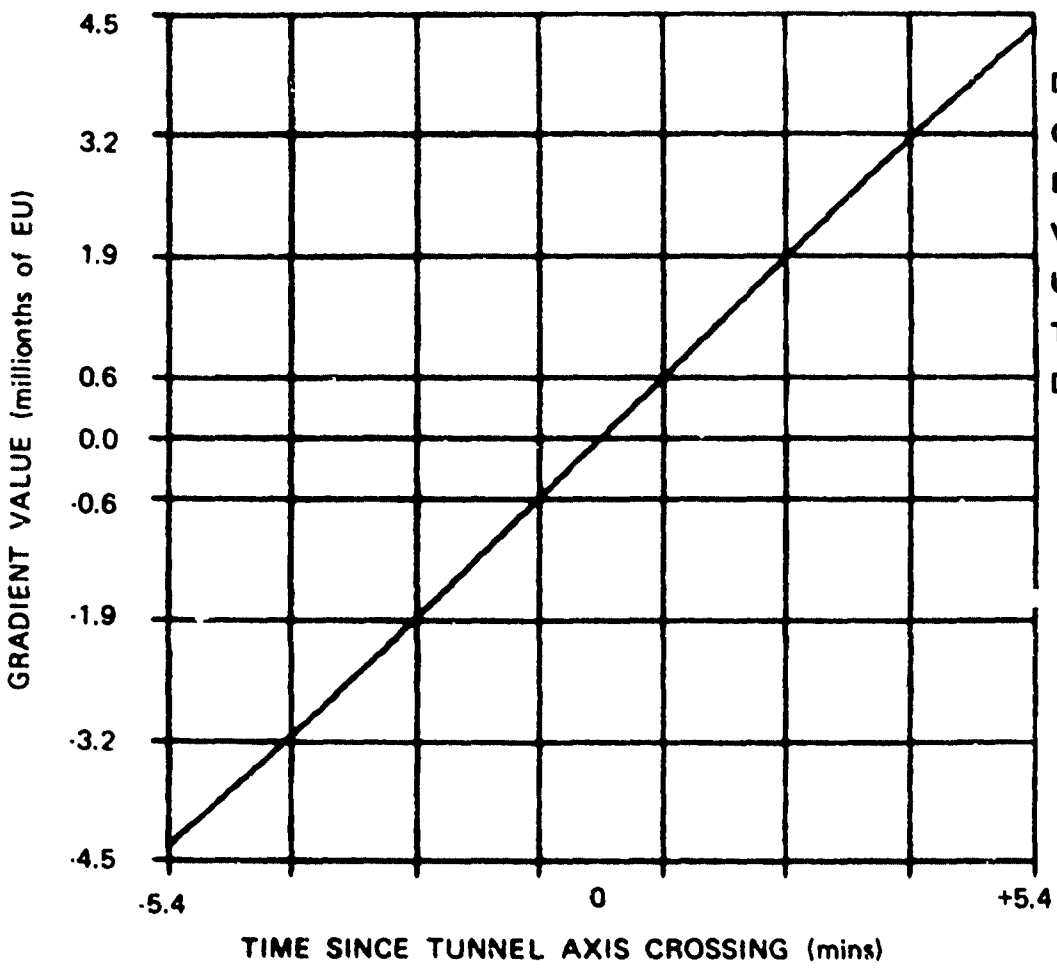
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23960

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

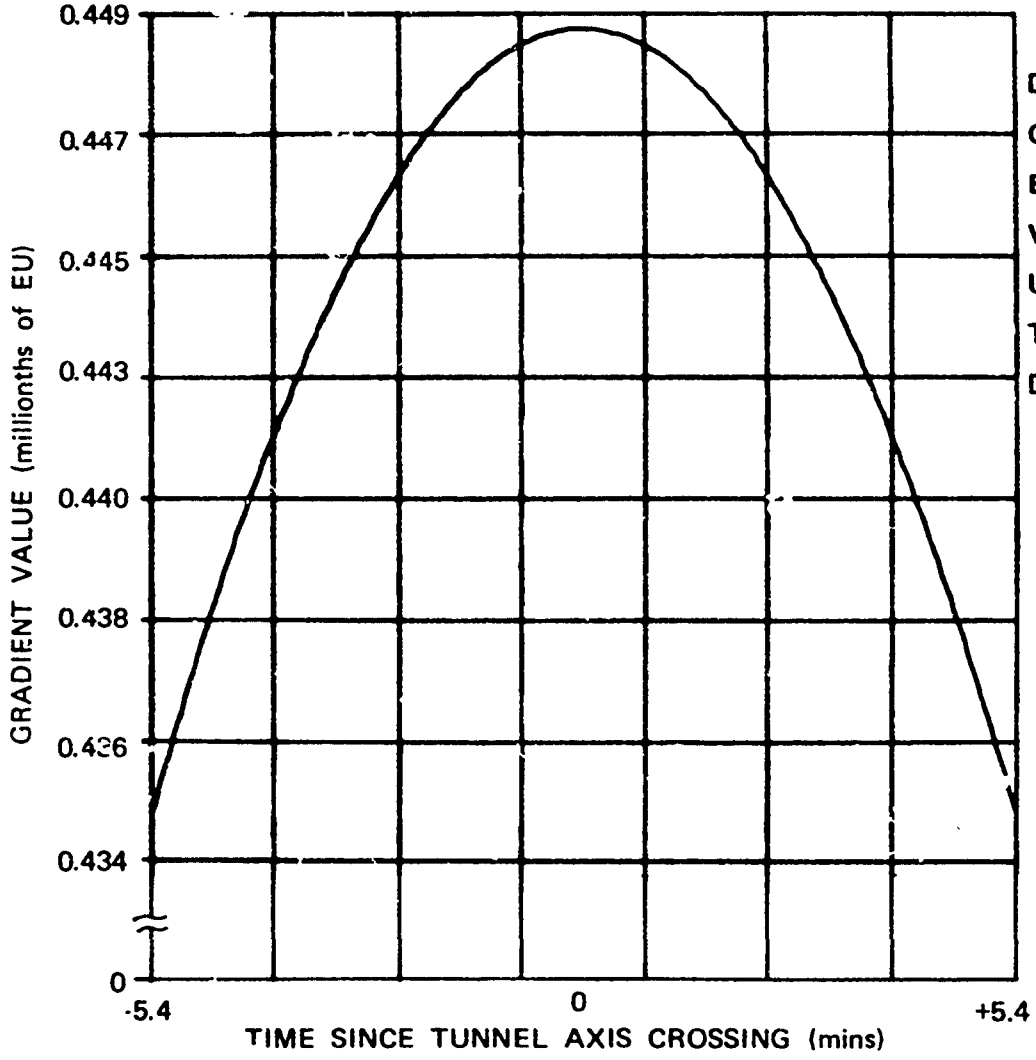
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23948



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{y\mu}$

ENCOUNTER ANGLE (θ) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

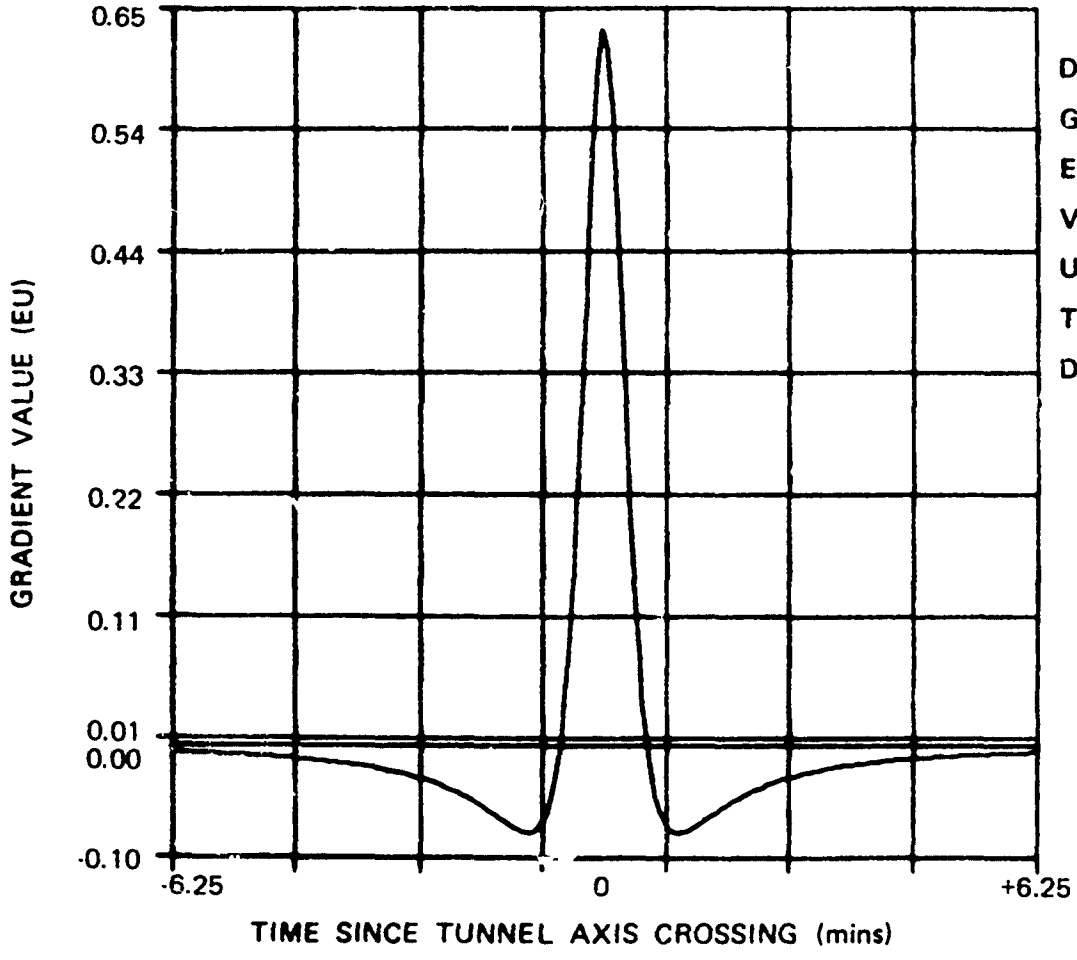
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 90 METERS
30° ENCOUNTER ANGLE

R-23968

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

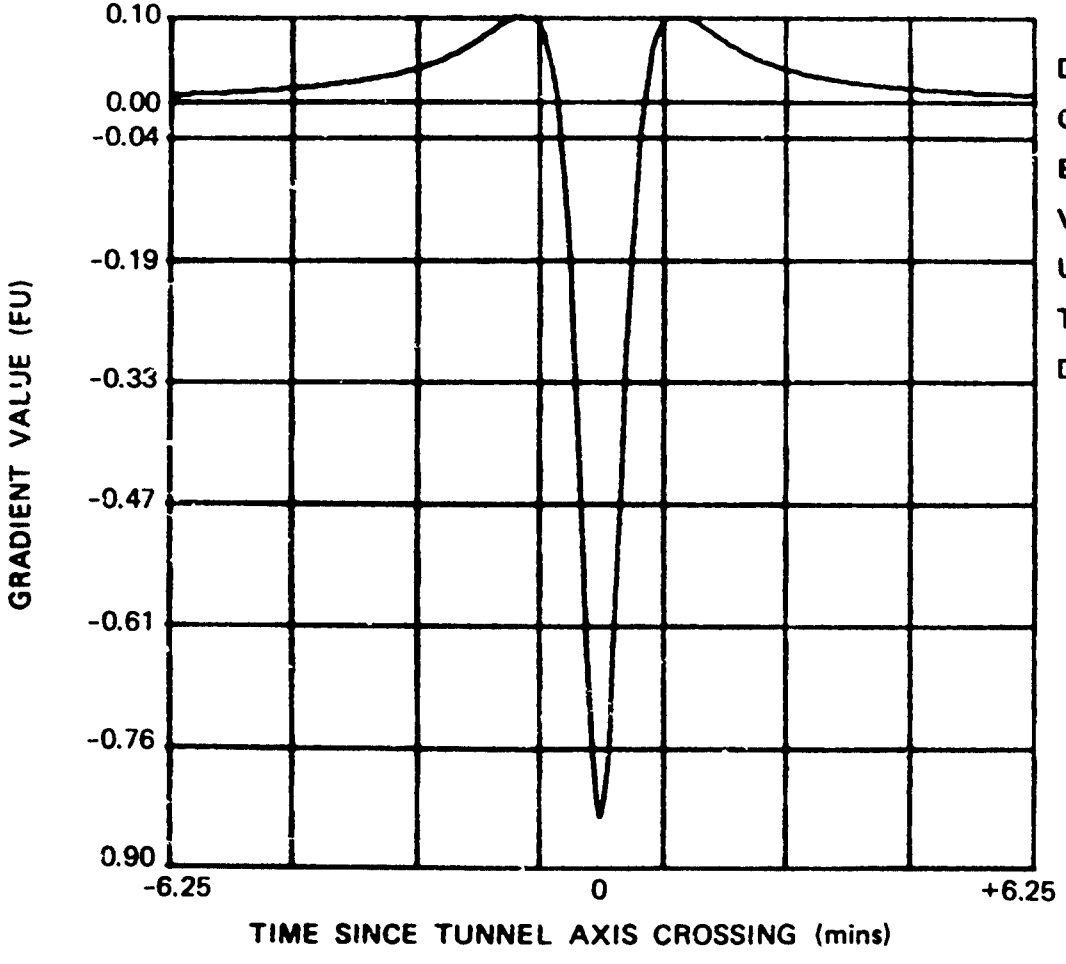
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23977

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

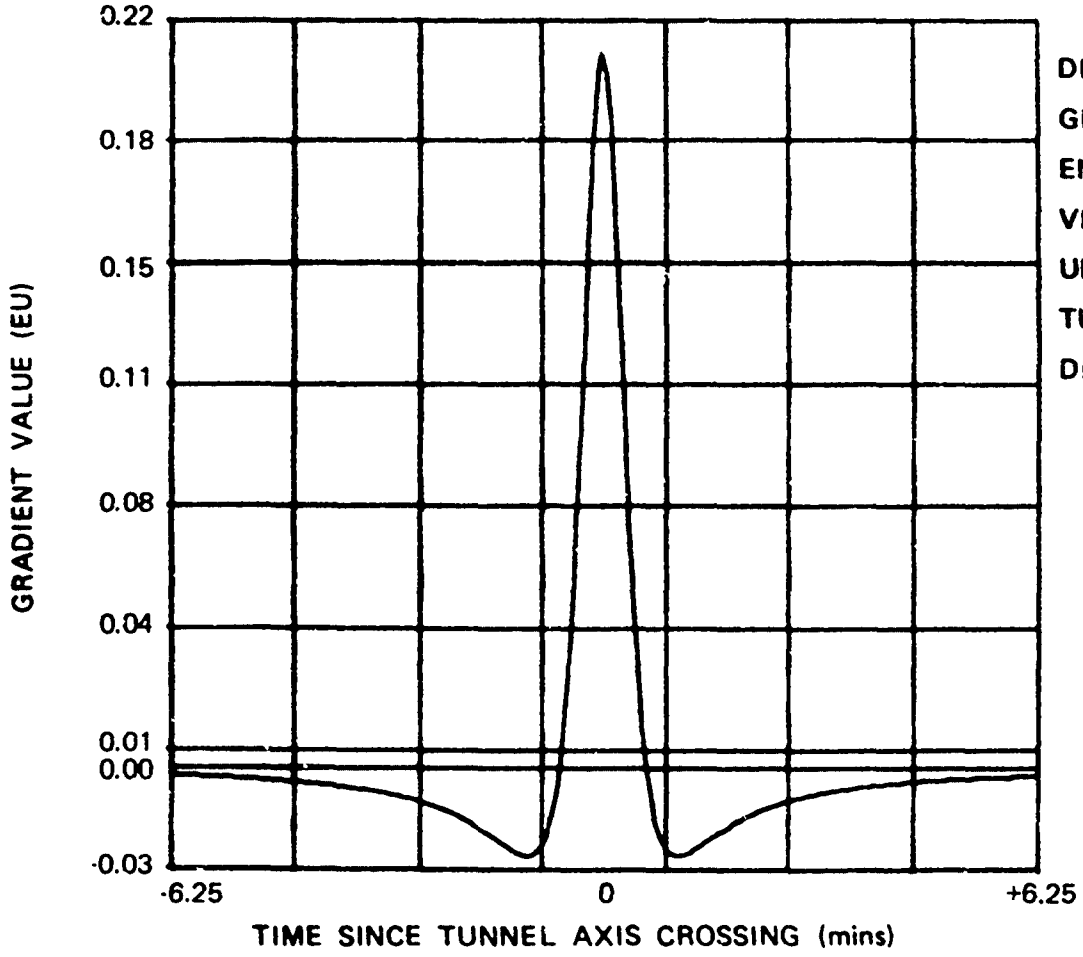
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23964

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\mu\mu}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

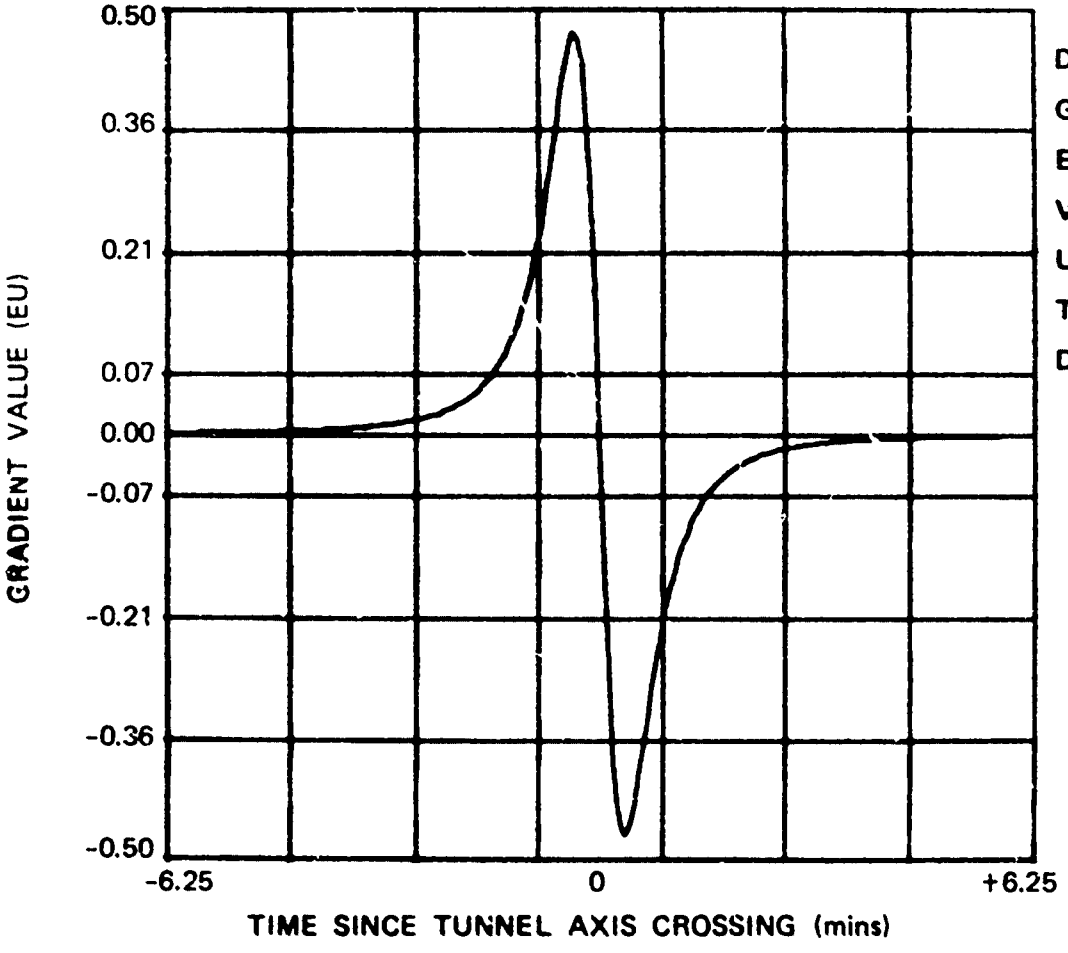
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23981

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

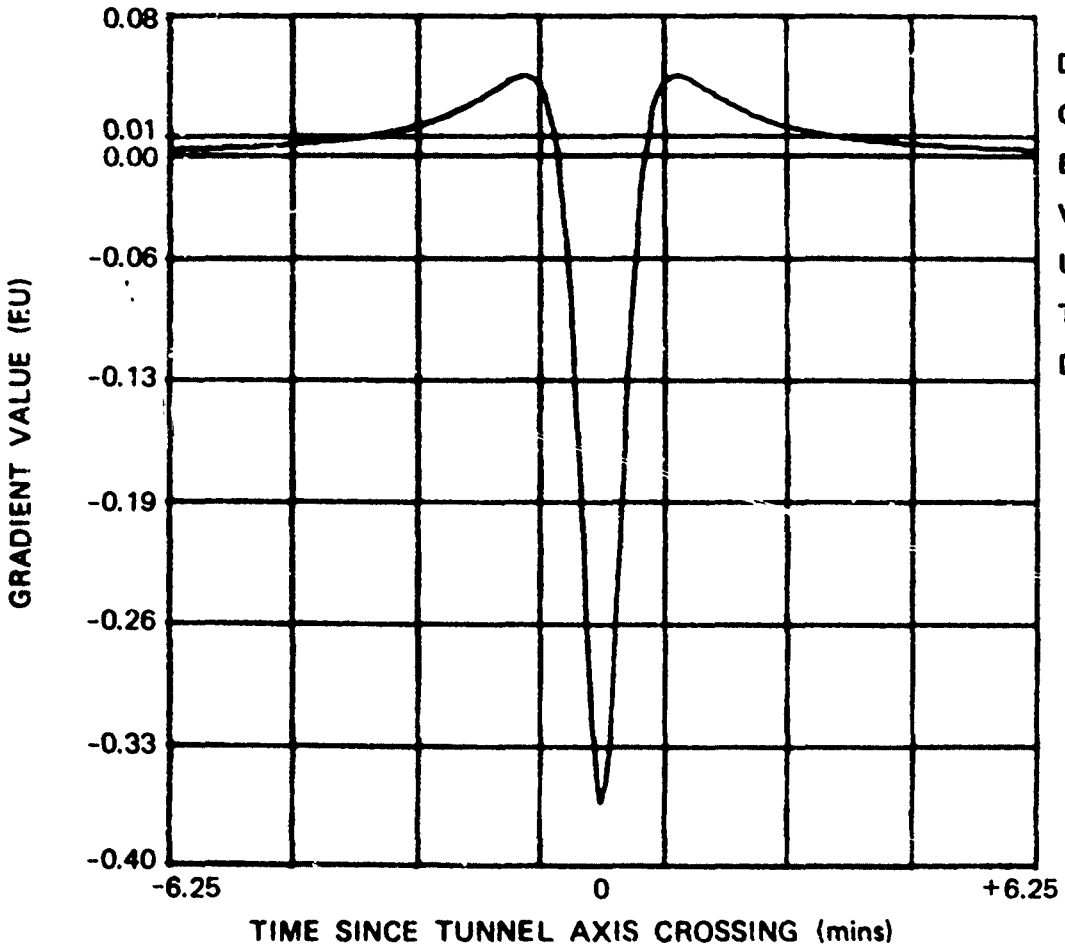
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23979

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

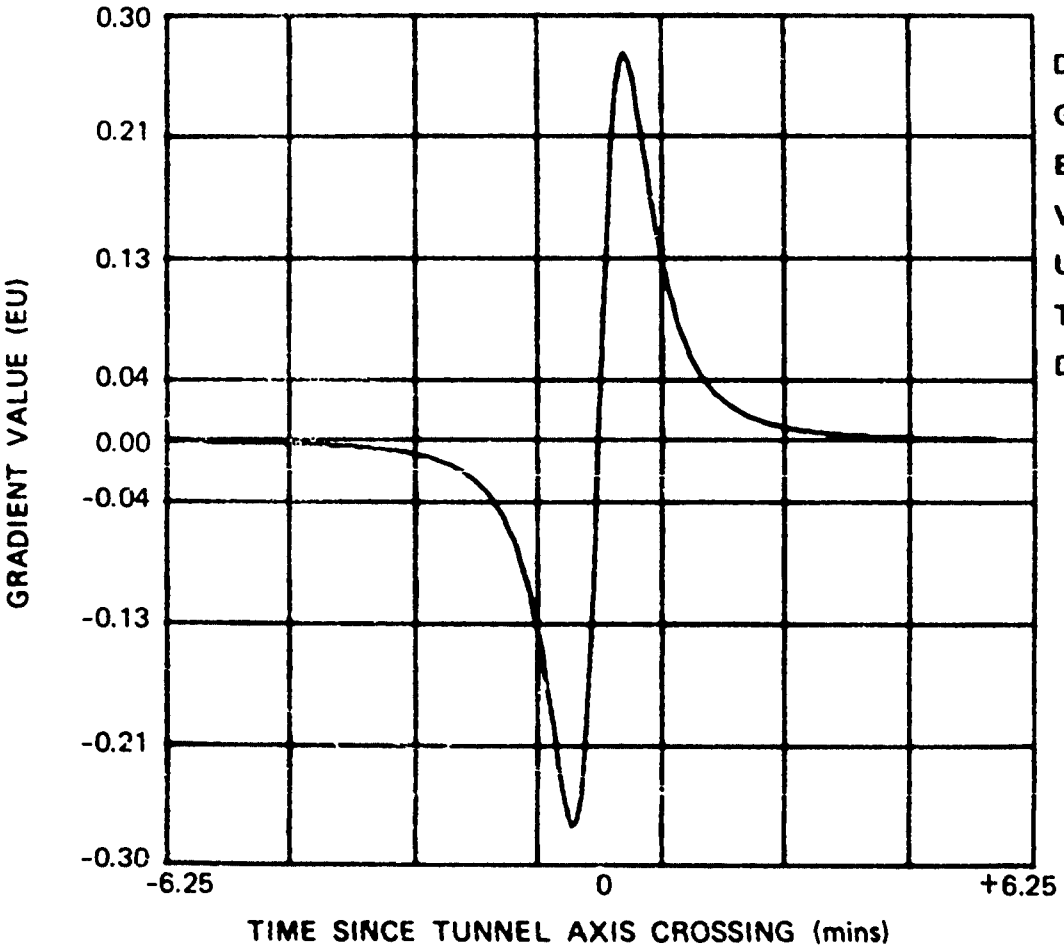
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23961



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = γ_{yu}

ENCOUNTER ANGLE (θ) = 30°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

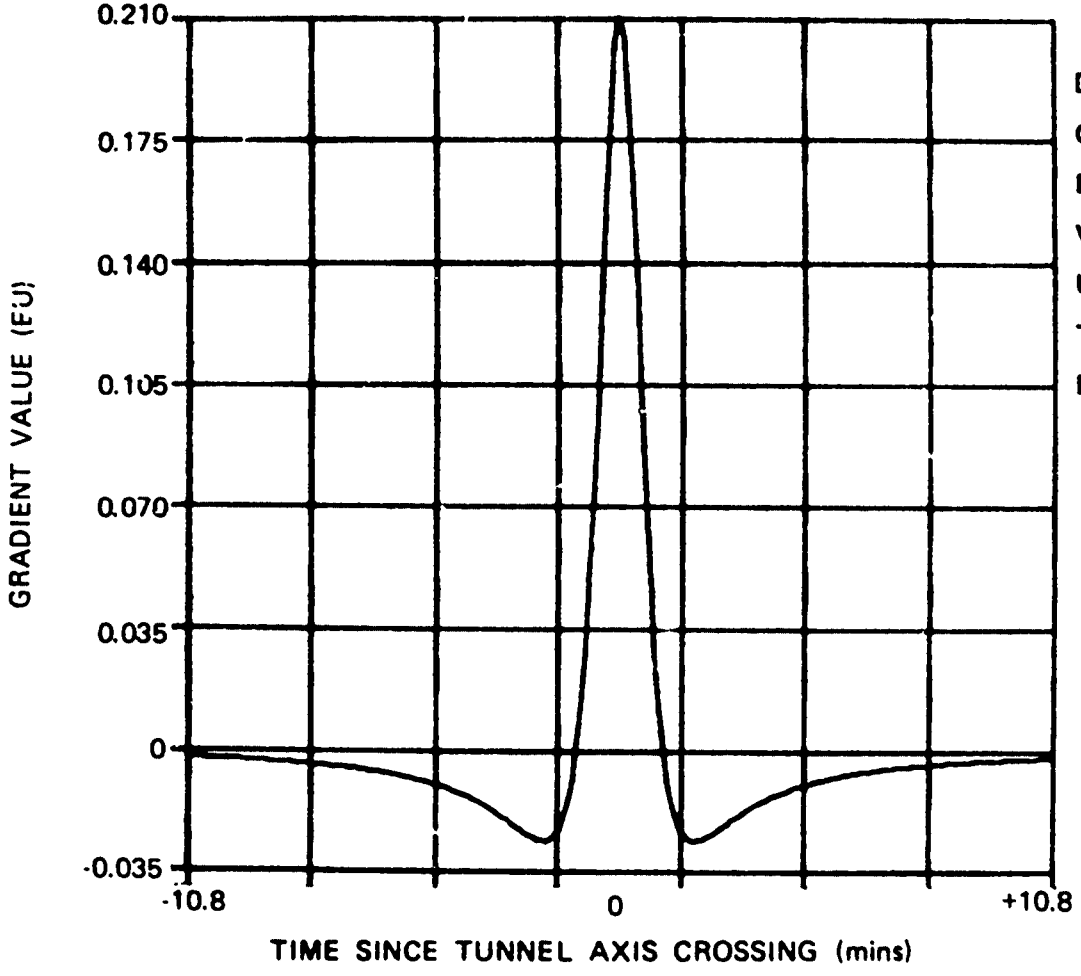
DISTANCE TO NEAREST END = 7 km

TASC

DEPTH = 90 METERS
60° ENCOUNTER ANGLE

R-23921

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\lambda}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

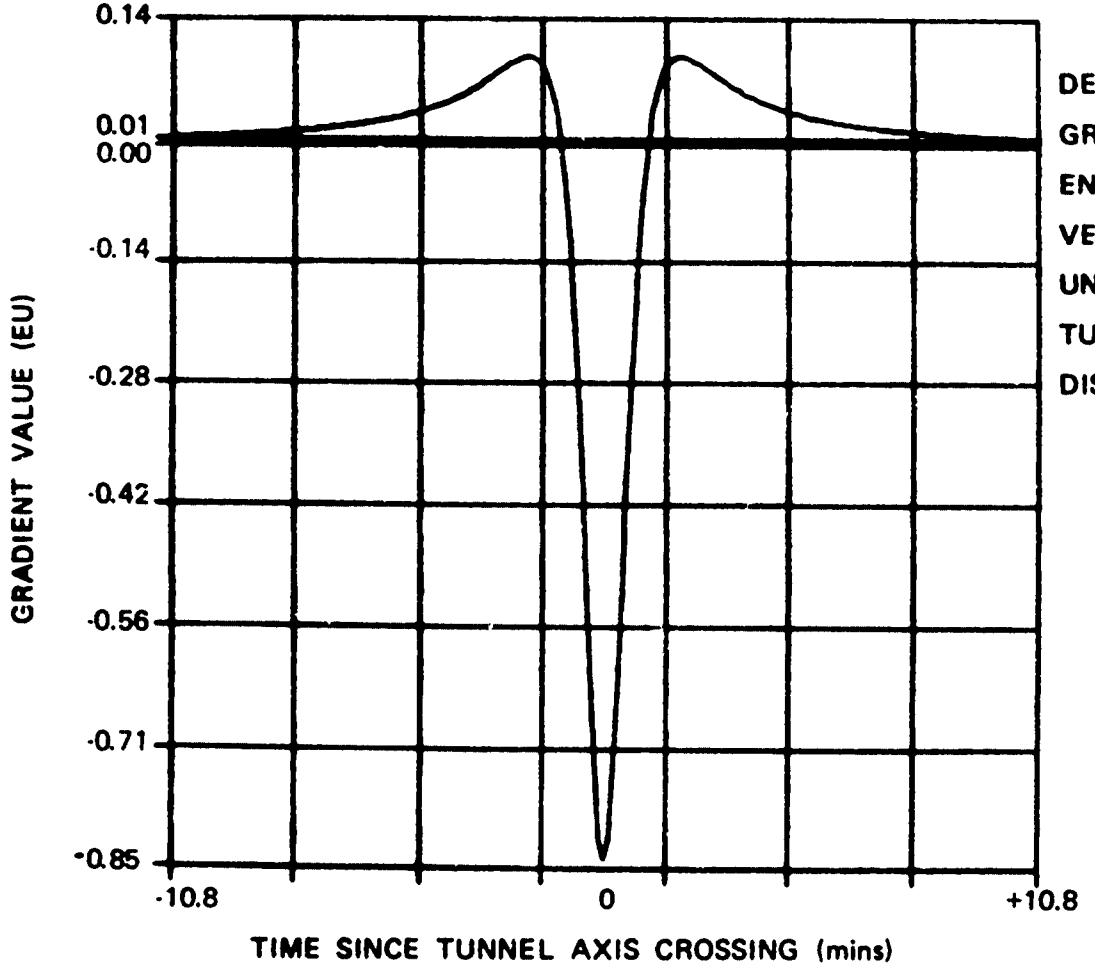
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23980

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = γ_{yy}

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

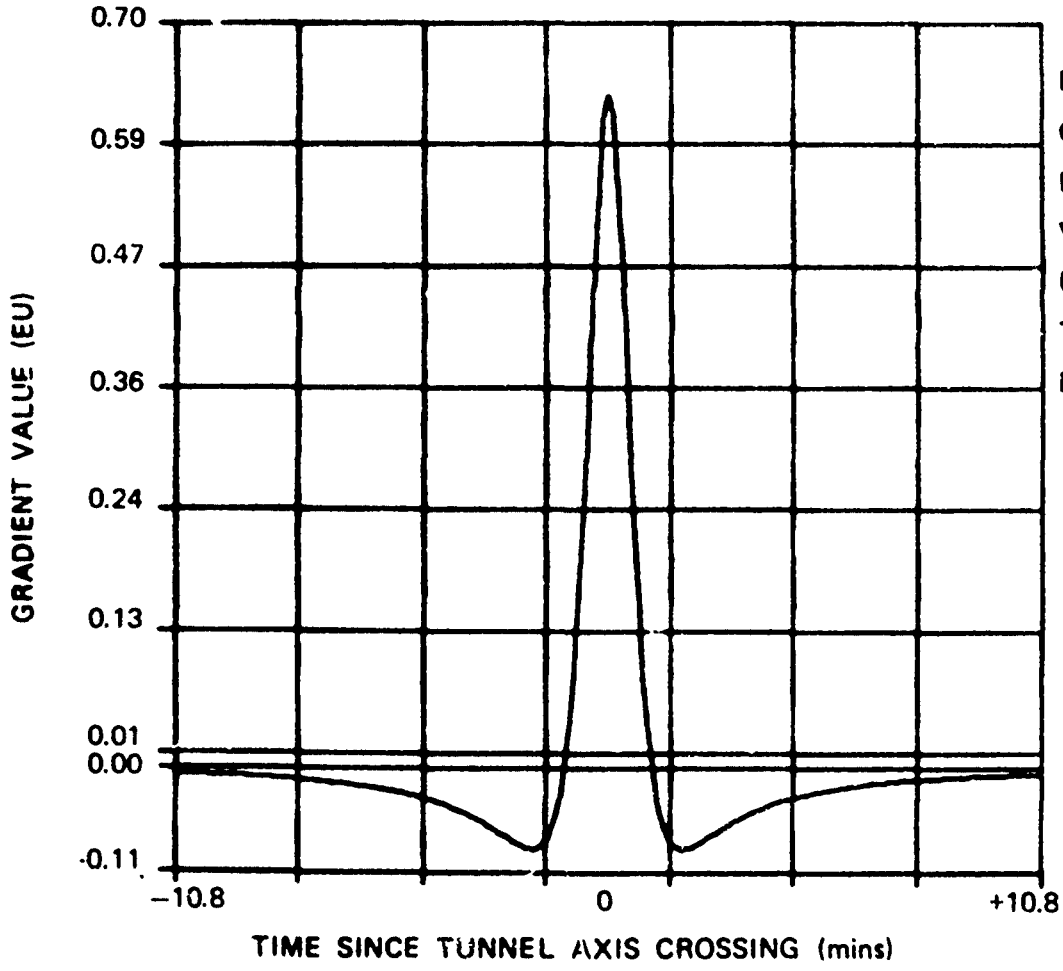
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23978

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = γ_{uu}

ENCOUNTER ANGLE (ε) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

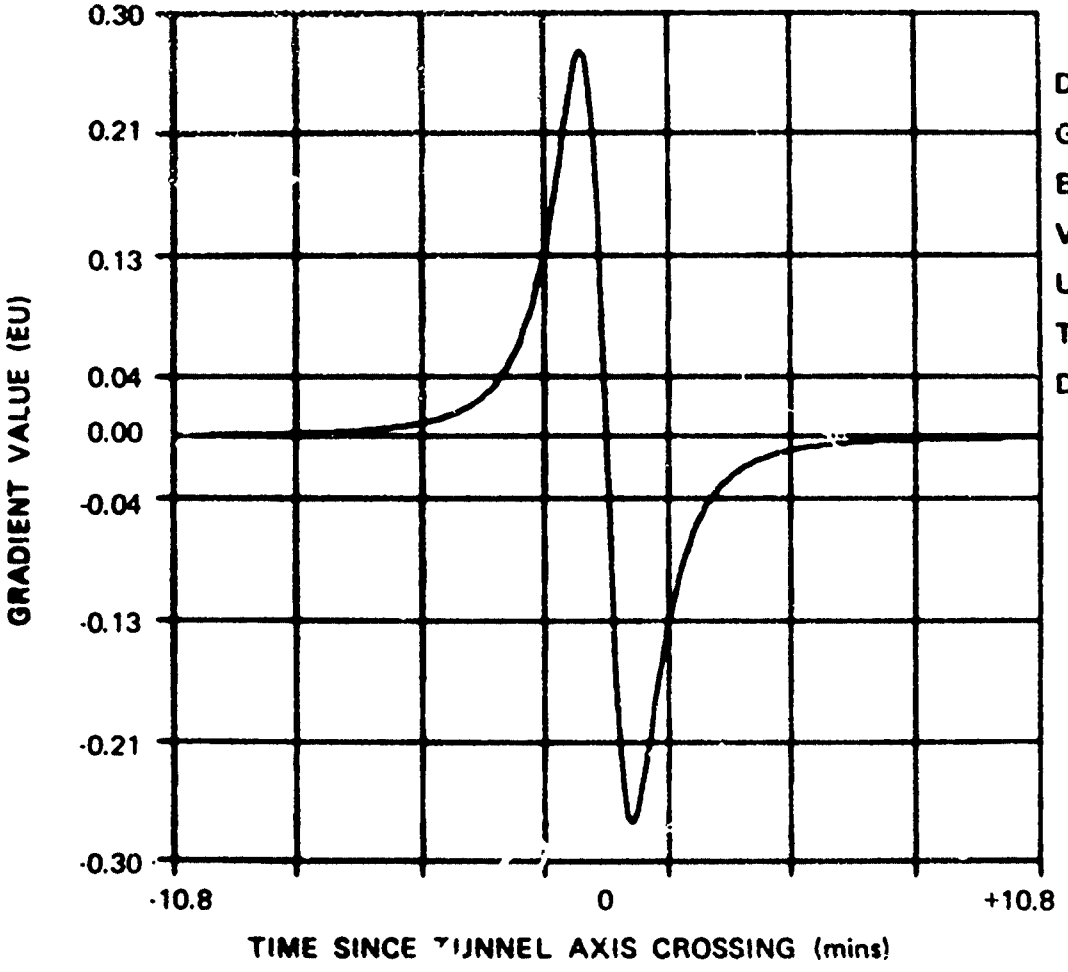
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23976

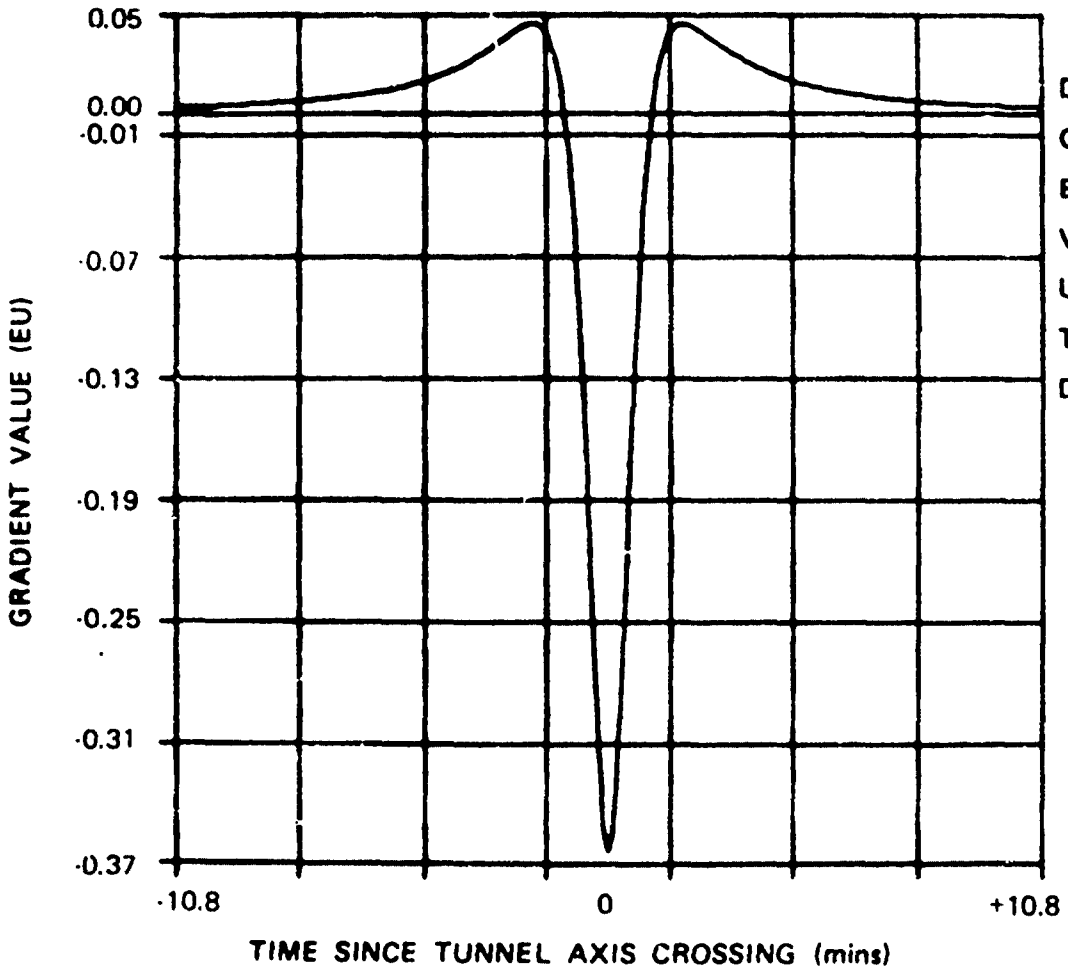


DEPTH TO TUNNEL AXIS = 90m
GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda y}$
ENCOUNTER ANGLE (θ) = 60°
VEHICLE VELOCITY = 10 km/hr
UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3
TUNNEL LENGTH = 16 km
DISTANCE TO NEAREST END = 7 km

TASC

SURFACE GRAVITY GRADIENT FROM TUNNEL

R-23-74



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{\lambda\mu}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

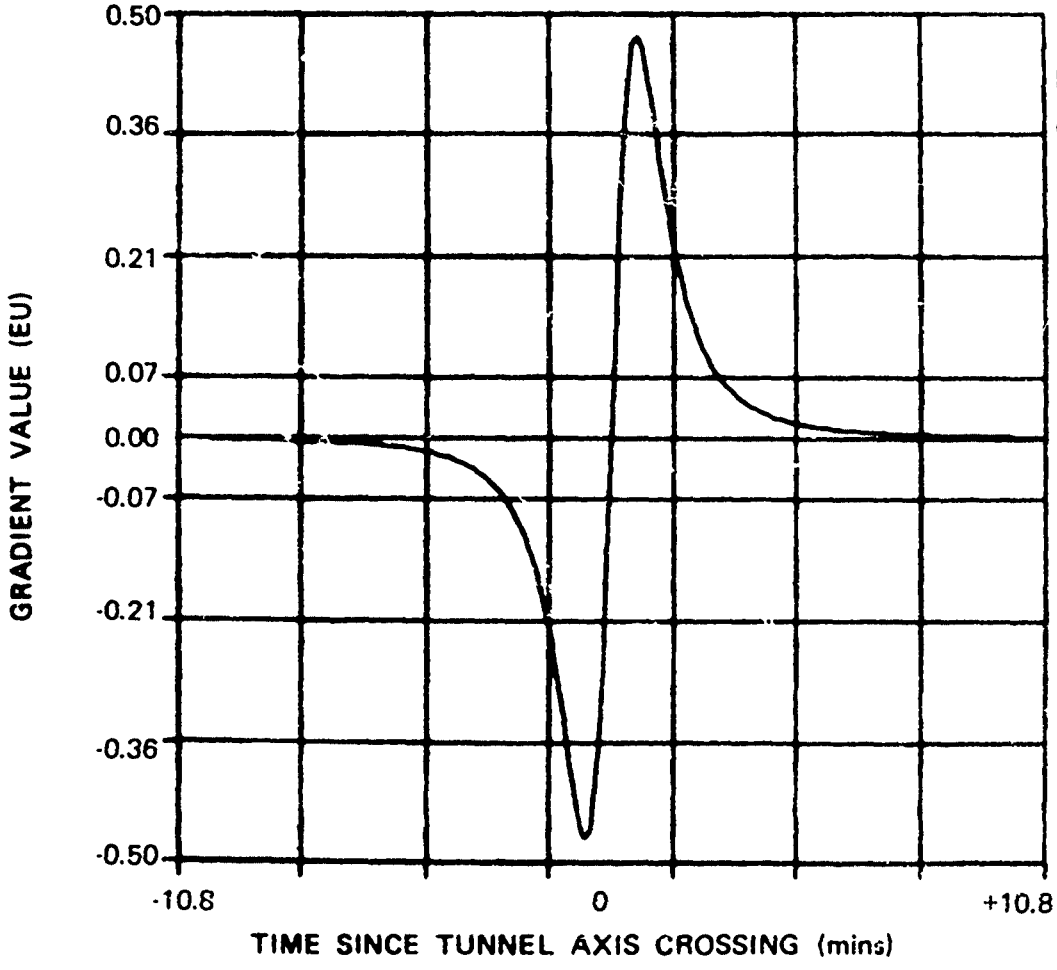
TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

TASC

R-23972

SURFACE GRAVITY GRADIENT FROM TUNNEL



DEPTH TO TUNNEL AXIS = 90m

GRAVITY GRADIENT ELEMENT = $\gamma_{y\mu}$

ENCOUNTER ANGLE (θ) = 60°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm^3

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km

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SCALING OF RESULTS TO DIFFERENT TUNNEL SIZES

R-23874

- GRAVITY AND GRAVITY GRADIENTS DEPEND LINEARLY ON THE AMOUNT OF SOURCE MASS

- TOTAL MASS OF A UNIFORM, CONSTANT LENGTH CYLINDRICAL BODY VARIES AS THE RADIUS SQUARED

- FOR CYLINDER OF RADIUS r (METERS), GRADIENTS AND GRAVITY VECTOR COMPONENTS DETERMINED IN THIS STUDY APPLY IF MULTIPLIED BY THE FACTOR

$$\left(\frac{r}{2.5}\right)^2$$

- SIMILARLY FOR A DENSITY OF THE SURROUNDING MEDIUM OTHER THAN 2.6 g/cm^3, RESULTS SHOULD BE MULTIPLIED BY THE FACTOR

$$\frac{\rho}{2.6}$$

WHERE ρ IS THE DENSITY IN g/cm^3

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SUMMARY AND CONCLUSIONS

SUMMARY

PEAK GRADIENT SIGNAL STRENGTH AT BEST AND WORST* ENCOUNTER GEOMETRY

R-23875

GRAVITY GRADIENT ELEMENT		VALUES OF θ FOR BEST AND WORST DETECTION		MAXIMUM VALUE OF GRADIENT (EU)					
				6 m DEPTH		30 m DEPTH		90 m DEPTH	
		BEST	WORST	BEST	WORST	BEST	WORST	BEST	WORST
INLINE GRADIENTS	$\Gamma_{\lambda\lambda}$ (ALONG-TRACK)	0°	60°	189	47	7.6	1.9	0.84	0.21
	$\Gamma_{\mu\mu}$ (CROSS-TRACK)*	60°	0°	142	$<10^{-5}$	5.7	$<10^{-5}$	0.63	$<10^{-5}$
	Γ_{yy} (VERTICAL)*	ALL θ		189	189	7.6	7.6	0.84	0.84
CROSS GRADIENTS	$\Gamma_{\lambda y}$ (ALONG-TRACK, VERTICAL)	0°	60°	123	61	4.9	2.5	0.55	0.27
	$\Gamma_{\lambda\mu}$ (HORIZONTAL PLANE)	45°	0°	95	$<10^{-5}$	3.8	$<10^{-5}$	0.42	$<10^{-5}$
	$\Gamma_{\mu y}$ (CROSS-TRACK, VERTICAL)*	60°	0°	106	$<10^{-5}$	4.3	$<10^{-5}$	0.47	$<10^{-5}$

*ENCOUNTER ANGLES (θ) CONSIDERED ARE 0°, 30°, 45°, 60°.

(NOTE: PEAK SIGNAL STRENGTH BECOMES EXCEEDINGLY SMALL FOR $\theta = 90^\circ$)

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CONCLUSIONS

R-23878

- GRADIOMETRIC DETECTION OF LARGE TUNNELS TO A DEPTH OF 30 m IS FEASIBLE USING MOVING BASE GRADIOMETERS WITH AN ACCURACY OF 1-10 EU (10 sec AVERAGING TIME)

- RELIABLE DETECTION OF LARGE TUNNELS DEEPER THAN 30 m IMPOSES MODERATELY SOPHISTICATED DATA PROCESSING REQUIREMENTS (e.g., MULTIPLE COMPARISONS AMONG GRADIENTS, OPTIMAL FILTERING, SIGNATURE MATCHING, etc.)

- DETECTION OF TUNNELS DEEPER THAN 90 m IS DIFFICULT

- SINGLE GRADIENT ELEMENT WITH GREATEST CONSISTENT SIGNAL STRENGTH REGARDLESS OF ENCOUNTER ANGLE IS THE VERTICAL, IN-LINE TERM

- AXIAL DIRECTION OF SHALLOW OR LARGE TUNNELS CAN BE ESTABLISHED IN A SINGLE PASS BY COMPARING MAGNITUDES OF ELEMENTS IN THE GRADIENT TENSOR (SUBJECT TO TUNNEL'S DEPARTURE FROM IDEAL GEOMETRY)

- MODERATE SHIFTS OF SURFACE CROSSING POINT TOWARD ONE END HAVE AN INSIGNIFICANT EFFECT UPON DETECTABILITY

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ADDITIONAL TOPICS OF INTEREST

R-23877

- MAXIMUM DETECTABLE DEPTH USING OPTIMAL FILTERING AND TAKING ALL RELEVANT ERROR SOURCES INTO ACCOUNT
- QUANTIFICATION OF CLOSENESS OF DETECTOR VEHICLE TRACK TO AXIAL DIRECTION BEFORE ONSET OF UNOBSERVABILITY
- DISTANCE BETWEEN CROSSOVER POINT AND TUNNEL END WHERE MODELED GRADIENTS (GAUSS' LAW + POINT MASS) DEVIATE SUBSTANTIALLY FROM ACTUAL GRADIENTS
- MORE COMPLICATED TUNNEL GEOMETRIES, VERTICAL SHAFTS
- OTHER DEPTHS AND ENCOUNTER ANGLES

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